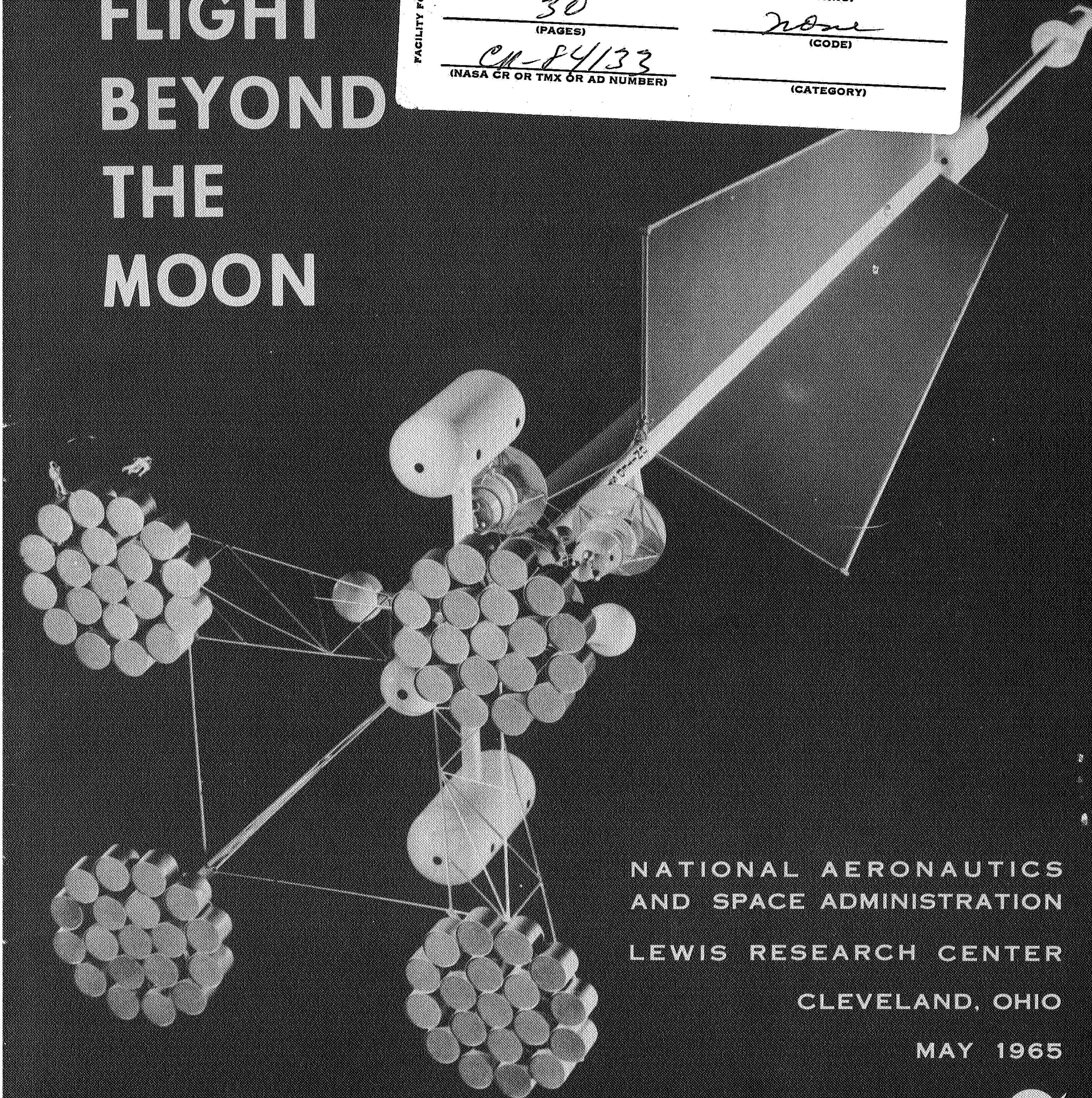
# SPACE FLIGHT BEYOND THE MOON





NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO

MAY 1965

NASA

# SPACE FLIGHT
# BEYOND THE MOON

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Electromagnetic Propulsion Division
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

# SPACE FLIGHT BEYOND THE MOON

Before man flies beyond the Moon, the nearby planets will be observed with instruments to obtain more information about conditions on these other worlds. We know, for example, little about the surface of Venus, because it is completely obscured by a thick cloud cover. An unmanned space probe, Mariner 11, has already been launched toward Venus. The instrumentation aboard Mariner 11 provided a great deal of information on the mysteries of the hidden surface of Venus and its atmosphere including the fact that very high surface temperatures may preclude the likelihood of life as we know it.

Astronomers looking at Mars, another close planetary neighbor, through telescopes have observed seasonal color changes on the planet's surface. Some eminent scientists conclude from this that plant life exists on Mars; the existence of plant life naturally raises questions of possible animal life. Further clues on the Martian makeup may be furnished by probes like Mariner IV, which was launched in November 1964.

Such instrumented probes are only the beginning. To conduct a full scientific exploration of the planets, man must journey to these alien worlds. In the course of this great adventure, science will discover much to add to our knowledge and understanding of the universe in which we live.

As with all new endeavors, the exact future of long-distance space flight is uncertain. Yet, within the confines of our rapidly expanding technology, we can make a reasonable prediction of how man may travel beyond the Moon.

## SOME BASIC IDEAS AND THEIR HISTORY

The rocket-powered spacecraft has the same general function as any transportation system; it must move people and materials from one place to another.

Booster rockets are used to launch spacecraft into orbit about the Earth. The high thrust[1] and comparative safety of chemical rockets make them the only available vehicle for this important first step in space flight.

From orbit about Earth, the spacecraft must thrust up and away from the gravitational field of Earth. Then the spacecraft must continue on in the gravitational field of the Sun until its planetary destination is reached. The chemical rocket is not ideally suited for manned flight beyond the Moon. It uses too much propellant. Large propellant consumption means that most of the spacecraft weight must be devoted to propellant. Not much room is left for payload, that is, the men,

[1]Thrust is the force exerted by the rocket engine.

instruments, and equipment carried on the rocket.

The chemical rocket has a high propellant consumption because it has a low exhaust velocity. Because the relation between propellant consumption and exhaust velocity is not easily seen, some explanation is required. As explained in the next section, an important quantity in rocket space flight is the "total impulse." This quantity is simply the rocket thrust multiplied by the thrusting time:

$$\text{Total impulse} = \text{Thrust} \times \text{Thrusting time}$$

Long-distance flights or fast flights require a high value of total impulse. An equation for thrust[2] is

$$\text{Thrust} = \text{Propellant flow rate} \times \text{Exhaust velocity}$$

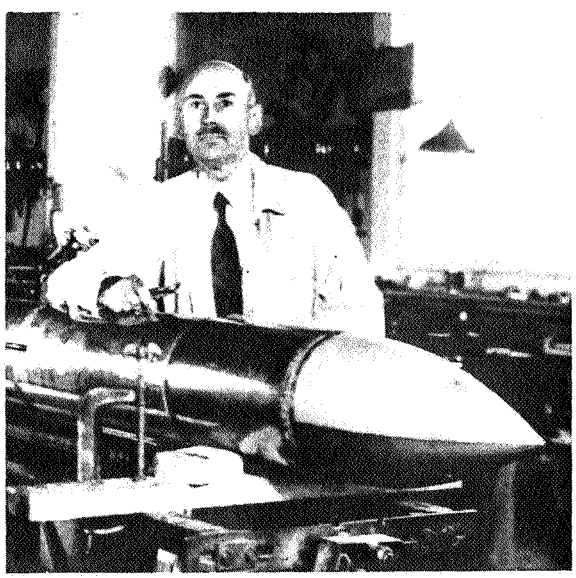
This expression for thrust may be used in the equation for total impulse:

$$\text{Total impulse} = \text{Propellant flow rate} \times \text{Exhaust velocity} \times \text{Thrusting time}$$

Propellant flow rate multiplied by thrusting time is really just the propellant mass at the beginning of the flight, and therefore

$$\text{Total impulse} = \text{Propellant mass} \times \text{Exhaust velocity}$$

For a particular space flight, a certain total impulse will be required. If the exhaust velocity is low, the propellant mass must be high. The chemical rocket has a low exhaust velocity and, therefore, needs a great amount of propellant.



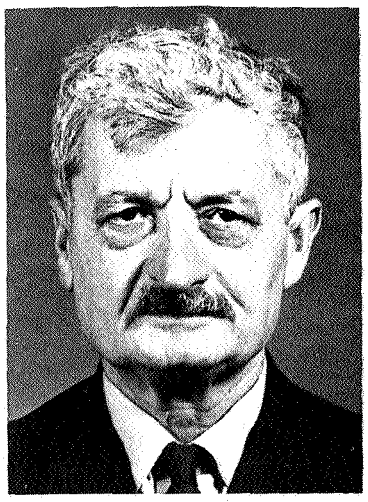
**Robert H. Goddard**

There is a basic reason for chemical rockets being limited to a low exhaust velocity. Even the best chemical propellants have a fixed energy per pound (i. e., heat of combustion). Since the chemical combustion process can release only so much energy per pound, the exhaust velocity is limited to about 4000 meters per second.

A number of other kinds of rocket-propulsion-system concepts have promise of much higher exhaust velocities than that of the chemical rocket. If these concepts can be made practical, heavy payloads could be carried in long-distance, fast, space flights.

Dr. Robert H. Goddard, the famous American rocket pioneer, realized that chemical rockets were limited in exhaust velocity. In 1906 he wrote in his laboratory notebook that this limitation in rocket ex-

[2] This equation is derived in the appendix.


Hermann **Oberth**

haust velocity might be overcome if electrically charged particles could be used instead of burnt gases. Electrically charged particles can be accelerated to extremely high velocities. "Atom smashers" such as cyclotrons can accelerate electrically charged particles almost to the speed of light. Dr. Goddard's idea of using electrically charged particles as a rocket exhaust was in essence the birth of electric propulsion.

The idea of electric propulsion was explored further by Professor Hermann Oberth, a German rocket pioneer. In a 1929 text, Professor Oberth described a possible electric rocket design in which high-voltage electric fields would accelerate charged particles to high exhaust velocities.

The acceleration of electrically charged particles requires a large quantity of electric power. In terms of propellant flow rate, the amount of electric power required is

$$\text{Power} = \frac{\text{Propellant flow rate} \times \text{Exhaust velocity}^2}{2}$$

In terms of rocket thrust,

$$\text{Power} = \frac{\text{Thrust} \times \text{Exhaust velocity}}{2}$$

Both of these equations show that electric power requirements increase as the exhaust velocity is increased. Suppose an electric rocket with a 1-pound thrust were to be built. For flights to the nearer planets, an exhaust velocity of 50,000 meters per second (about 100,000 mph) would be best for some electric rockets. More than 100,000 watts of electric power[3] are needed to accelerate enough charged particles to 50,000 meters per second in order to produce 1 pound of thrust. Such quantities of electric power could light thousands of electric light bulbs or run hundreds of electric washing machines.

In the time of Dr. Goddard and Professor Oberth, electric powerplants were very heavy. Conventional powerplants are still too heavy for use in electric rocket spacecraft, because they would require large amounts of coal, oil, or gas. Conventional boilers, turbines, and generators would also add greatly to the weight of a self-contained powerplant for space flight. Such powerplants are so heavy that very little payload could be carried.

The advent of practical atomic power wrought a great change in the future of electric propul-

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[3]

$$\text{Power} = \frac{\text{Thrust} \times \text{Exhaust velocity}}{2}$$

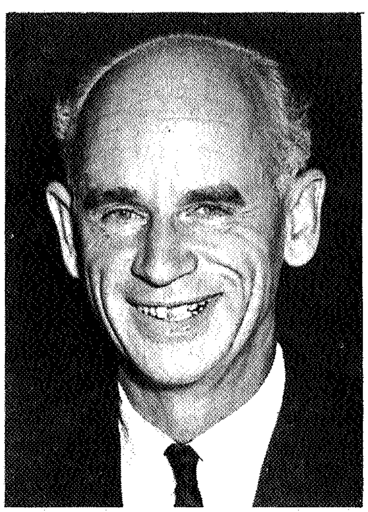
and 1 pound of thrust = **4.45** newtons; therefore,

$$\text{Power} = \frac{4.45 \text{ newtons} \times 50{,}000 \text{ meters per second}}{2}$$

Since 1 watt = 1 joule per second = 1 newton × meters per second, power = 110,000 watts.

L. R. Shepherd

A. V. Cleaver



Ernst Stuhlinger

sion for space flight. As early as 1948, two British scientists, Dr. L. R. Shepherd and Mr. A. V. Cleaver, suggested that controlled nuclear fission could provide the lightweight power source needed for electric rockets. They described an electric-power generation system in which a nuclear fission reactor would heat a fluid to a high temperature. This fluid would drive a turbine that would then drive an electric generator. This generator would, in turn, provide the electricity required to accelerate charged particles to a high exhaust velocity. Small amounts of nuclear fuel can provide very large amounts of power for long times. Although reactor structures and shields were quite heavy when Shepherd and Cleaver first proposed their plan, nuclear-energy technology has advanced rapidly, and their ideas appear more practical today. The development of lightweight nuclear turboelectric systems for space propulsion power is one of today's most challenging problems. The solution of this problem may be one of the keys to practical interplanetary travel.

Once the theoretical feasibility of electric powerplants for space flight had been established, serious thought began to include another essential part of an electric spacecraft - the electric rocket engine or thrustor. The first detailed discussion of the electric rocket engine was prepared in 1954 by Dr. Ernst Stuhlinger, pioneer in electric propulsion. In his papers, Dr. Stuhlinger proposed designs for a cesium-ion engine, which is one of the types of electric rocket engine being tested today.

Many scientists and engineers have been working on electric propulsion for space flight since 1957. Research on electric propulsion has progressed to the point where electric rocket engines have actually been tested during short-duration space flights. Much more research and development remains, particularly on advanced propulsion systems, which convert nuclear to electric energy in new and unique ways.

## PROPULSION IN SPACE

Man is used to living and moving about on the Earth's surface. His principal experience with gravitational fields is that things have weight and that falls from heights hurt. Compared with the gravity on Earth's surface, the gravitational field in the solar system is extremely complicated. The gravitational field of the solar system can be represented by the gravitational potential as shown by figure 1. This gravitational potential field may be thought of as a huge circular depression with the Sun at the bottom. Each of the planets is located at the bottom of its "gravity depression," which accompanies the

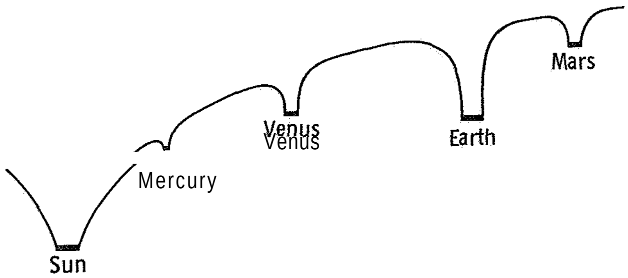


Figure 1

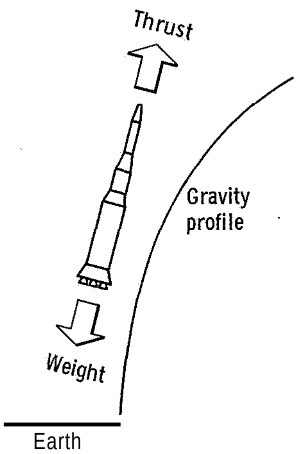


Figure 2.

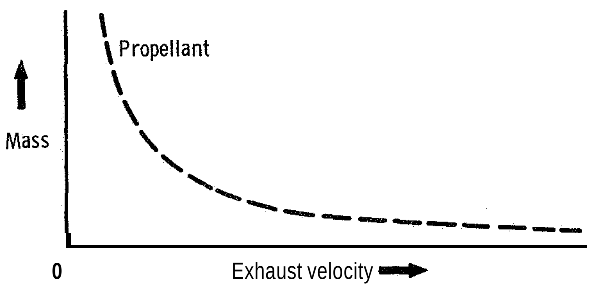


Figure 3.

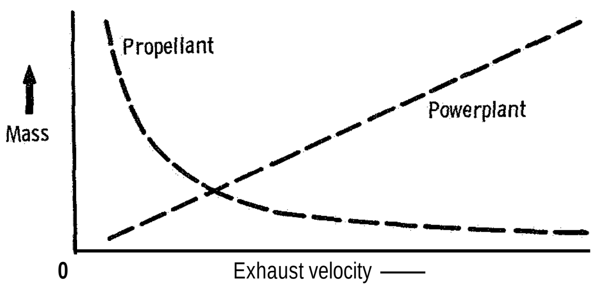


Figure 4.

planet in its path about the Sun, The gravitational field is quite invisible, but it exerts a decisive force on any objects within its domain. This force is proportional to the slope of the field at the location of the object. In the steep parts of the field, the force is very great, just as a sled slides the fastest on the steepest part of a snowy hill.

We live at the bottom of a deep, invisible gravity pit, which we must somehow climb out of to reach other planets. There are no ladders, steps, or antigravity machines available; man must propel himself with a rocket spacecraft. If the rocket is to rise directly up the "hill" (gravity profile), its thrust must be greater than its weight (fig. 2). If the thrust is substantially greater than the weight, the rocket will accelerate and pick up speed. If the thrust is applied for a sufficient time, the rocket will pick up enough speed to coast on up the "hill" a little farther. This characteristic can be given a value called total impulse:

Total impulse = Thrust × Thrusting time

(Total impulse has been discussed in the previous section.) The greater the total impulse, the farther up the hill the spacecraft will go. In general, the longer the distance or the faster the trip, the higher the total impulse must be.

The chemical rocket has an upper limit to its exhaust velocity; for this reason, a large propellant mass must be used for long-distance flights that require a large total impulse. The electric rocket has a much higher exhaust velocity, with the result that much less propellant is needed.

The propellant mass required for a particular space flight (i. e., a particular total impulse) can be shown on a graph (fig. 3). The electric power requirement, however, increases as the exhaust velocity increases. If the electric powerplant mass is directly proportional to its power output, the powerplant mass can also be shown on the graph as in figure 4. The sum of the propellant

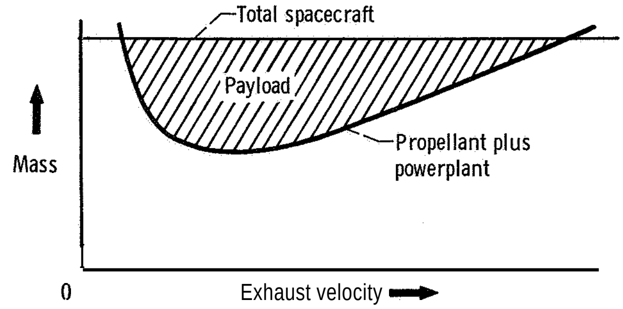


Figure 5.

and the powerplant masses can now be shown with respect to the total spacecraft mass (fig. 5). The payload mass is the shaded portion. There is a lower limit for the exhaust velocity; if the exhaust velocity is less than this lower limit, the propellant will be consumed too quickly, and the spacecraft will not reach its destination. If the exhaust velocity is too high, the electric powerplant will have too much mass and the spacecraft cannot be built. It is evident that the best exhaust velocity to use is that which will allow the most payload to be carried. For trips to the nearest planets with electric rockets, this optimum exhaust velocity is almost always between 20,000 and 100,000 meters per second.

If a spacecraft is to take off from the Earth's surface, its thrust must be greater than its weight. For such a flight, the electric-rocket thrust would have to be much greater than the weight of the powerplant. The principles described so far can be used to show that extremely lightweight powerplants would be required, for example, of the order of 1/10, 000 pound per watt. Thus, a powerplant with an output of 1000 watts could weigh only a few ounces. Space electric powerplants currently under development are hundreds of times heavier than this. Consequently, electric spacecraft currently being studied cannot be expected to take off from Earth. They must be boosted into orbit about Earth by chemical rockets.

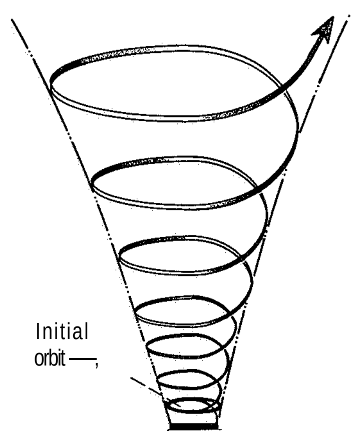


Figure 6.

Once in Earth orbit, electric spacecraft could fly very well with a small thrust. The electric rocket engine would be started in orbit and the ship would slowly climb up the Earth's gravitational field in a spiral path (fig. 6). Of course, this imaginative diagram only illustrates the principle of slow spiraling away from the Earth's gravitational field. Actually, the ship would follow a spiral path in one plane (fig. 7). Since the gravitational field is invisible, it must be imagined in this drawing. As the electric rocket continued thrusting, the spacecraft would continue around the Earth in an ever-widening spiral until it effectively left the Earth's gravitational field. More precisely, it would enter a region in space where the gravity pull of the Earth is slight compared with the gravity of the Sun.

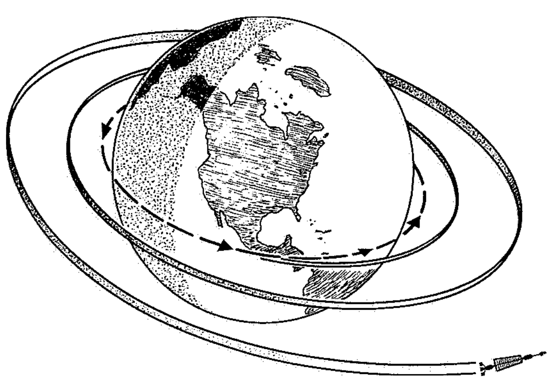


Figure 7.

In this description of flight paths not much has been said of the actual speed of the spacecraft. Speed can be a misleading idea in the complex gravitational field of the solar system. For example, if a chemical rocket were to be shot straight up from the Earth's surface, it would have to achieve a speed of about 25,000 miles an hour to escape. This assumes that the rocket would thrust furiously for a short period, perhaps 15 minutes, and would then coast the rest of the way. The rocket would be coasting up out of our "gravity pit," and the farther away from Earth it coasted, the slower it would go. If the gravitational field of the Sun were ignored, the ship would slow almost to *a* stop far from Earth; that is, it would stop with respect to the Earth, which is moving about the Sun at speeds of nearly 67,000 miles per hour. A spaceship launched from the Earth also has that speed with respect to the Sun. Furthermore, the Sun is rushing through space; therefore, the ship also has that speed.

Satellites decrease in speed as they move away from Earth. A low-level satellite moving at 17,000 miles per hour takes about $1\frac{1}{2}$ hours to orbit the Earth. The Moon is a satellite of the Earth, too. It takes about 27 days to orbit the Earth, moving at a speed of about 2300 miles per hour. Thus, the Moon travels almost eight times slower with respect to the Earth than the low-level satellite.

The electric rocket is also affected by this principle. It would move more slowly farther away from Earth.[4] The work being done by the powerplant and the engine would be used in raising the ship up and out of the Earth's gravitational field. This work would not increase the ship's speed. The chemical rocket booster would provide the initial spurt in speed required to place the electric spacecraft in orbit. From there on, the electric rocket could provide the rest of the propulsion.

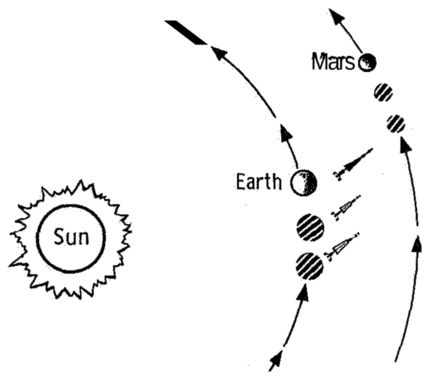


Figure 8.

When the electric spacecraft is hundreds of thousands of miles from Earth, the gravitational field of Earth becomes weaker than the gravitational field of the Sun. During the transition from dominance of Earth's field to dominance of the Sun's, the ship is attracted to both Earth and the Sun. This situation is so complicated that the ship's path must be calculated on a digital computer even when the rocket is coasting. When free from Earth, the ship still has the speed of Earth in addition to its speed with respect to Earth (see fig. 8). The electric spacecraft continues to thrust in the direction shown. Because it still has the speed impetus from Earth, it tends to move on around the Sun. The energy provided by the continued thrusting causes the ship to move farther away from the Sun, but because it is farther away from the Sun, it falls behind Earth in the race around the Sun. The initial speed provided by the Earth is important to any spacecraft. Without it the ship would fall into the Sun.

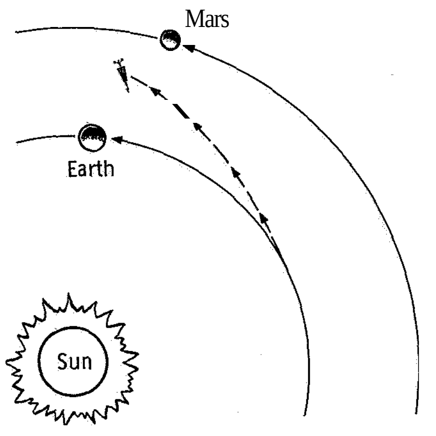


Figure 9.

When the ship is about halfway to Mars, it is orbiting the Sun faster than Mars because it is closer to the Sun. The ship must be swung around (fig. 9) in order to apply

[4]This is true for spacecraft propelled with the nuclear-turboelectric systems presently envisioned. If much lighter propulsion systems could be built, the thrust would be greater and *the* spacecraft could accelerate to high speeds in the Sun's field. The advanced propulsion systems to be discussed later in this paper could provide such acceleration.

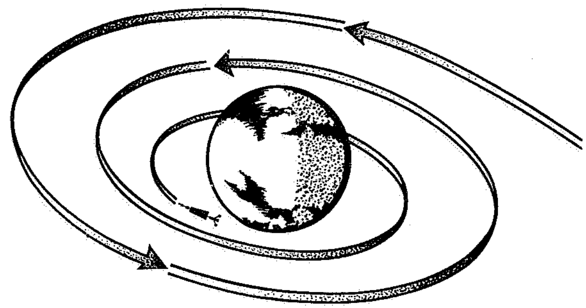


Figure 10.

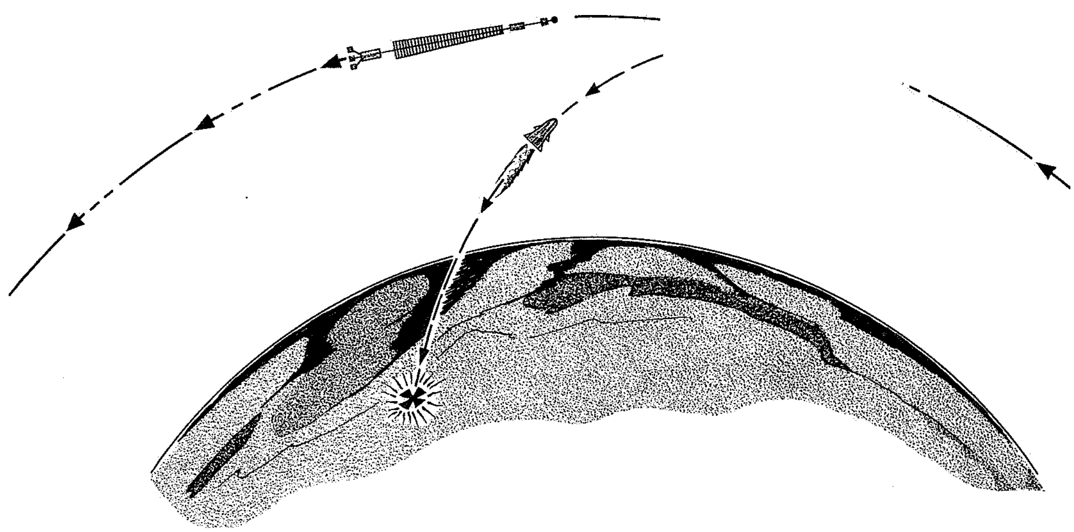


Figure 11.

the reverse thrust necessary to slow it down to the speed of Mars. When the ship reaches the gravitational field of Mars, it must spiral down to a satellite orbit around Mars (fig. **10).** The ship continues to thrust backward as it spirals down.

The low thrust of the electric rocket will not permit a direct landing on Mars. If the ship is manned, the crew may descend to the surface of Mars in a chemical rocket while the electric spacecraft continues to swing around Mars in its satellite orbit (fig. 11).

Now that some principles of space flight have been described in an imaginary trip to Mars, it is possible to discuss electric rocket engines within the framework of these principles.

## ELECTRIC ROCKET ENGINES

The electric rocket engine, or electric rocket thrustor, is a device that converts electric power and propellant into a forward-directed force, or thrust. The general principle **of** operation is illustrated by figure 12. Electric power is used to accelerate propellant material to a high exhaust velocity. This velocity produces a forward thrust force. By one of Newton's laws of motion, there must be an equal and opposite reaction for every action. The forward thrust force is the equal and opposite reaction to the backward

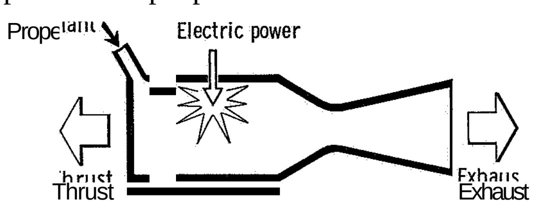



Figure 12.

Figure 13.

exhaust force. Action and reaction works in a vacuum, too, because air is not involved in this principle. Thrust is produced because material is being thrown out the back, not because anything is pushing against air. As a matter of fact, most electric rocket engines will not work in air; they will work only in a vacuum. Actually, air just gets in the way of the exhaust.

The principle of rocket-engine thrust can be illustrated by the following example. A skater stands upright with a bowling ball held near his body. He pushes the bowling ball away. The ball goes flying one way, and he will certainly go flying the other way (fig. 13). The faster the skater pushes the ball away, the harder he will be pushed the other way. Another illustration of this principle is the garden hose. Without the nozzle, the water runs out easily. With the nozzle, the water comes out with a high velocity, and, unless the hose is held firmly, it will thrash about because of the thrust force. All rockets work on this principle.

There are three general types of electric rocket engine: electrothermal, electromagnetic, and electrostatic. In the electrothermal rocket (fig. 14), electric power is used to heat the propellant to a high temperature. The heating may be accomplished by flowing the propellant gas through an electric arc or by flowing the propellant gas over surfaces heated with electricity.

The electrothermal rocket is similar in some respects to the chemical rocket. Although there is no combustion, the propellant gas is heated to high temperatures and expanded through a nozzle to produce thrust. This rocket can achieve exhaust velocities higher than those of chemical rockets because the energy added to the gas may be larger than the energy of combustion. Breakup or dissociation of the propellant gas molecules, which absorbs energy without raising gas temperature very much, places an upper practical limit on the amount of energy that can be added to the propellant. Other factors, such as erosion caused by the arc and material failure at high temperature, also limit the exhaust velocity.

The electric-arc type engine is in a fairly advanced state of development. It has an efficiency[5] of about 40 percent to date, and some engines are being made ready for test flights in space. Because the exhaust velocity of the electrothermal rocket engine is limited, it probably will not be used for interplanetary space flight.

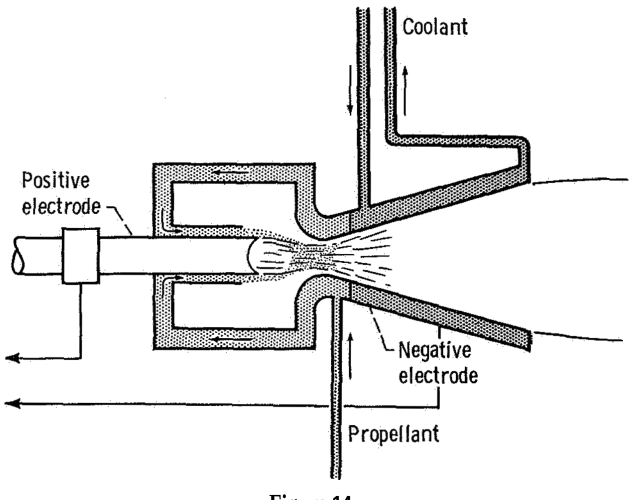


Figure 14.

[5]**Efficiency** is a figure of merit of engines. It is the efficiency with which electric power and propellant mass are used to produce thrust. An engine with an efficiency of 100 percent would convert all the electric power into thrust by accelerating every propellant particle to the desired exhaust velocity.

$$\text{Electric-rocket-engine efficiency} = \frac{\text{Thrust}^2}{2 \times \text{Propellant flow rate} \times \text{Electric power used}}$$

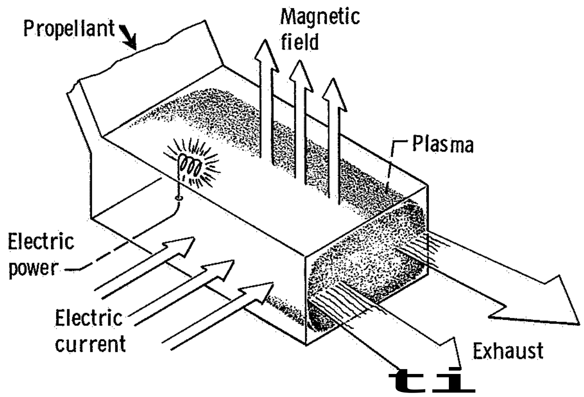
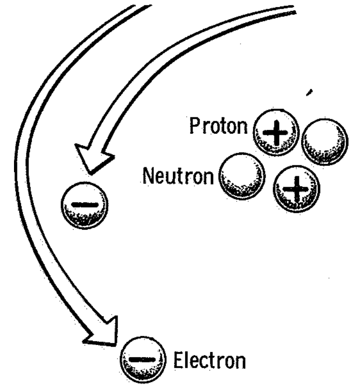


Figure 15.



'Figure 16.

This engine, however, probably could be used for short-range space flights as far away as to the Moon. It could also be used **for** attitude control of large spacecraft.

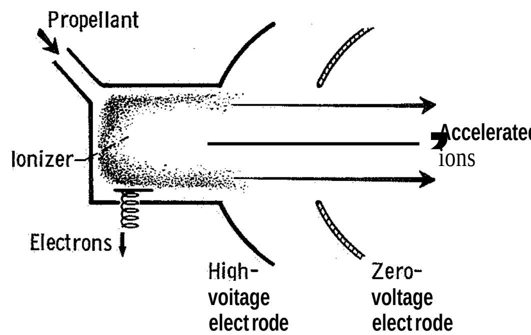


Figure 17.

The second general type of engine is the electromagnetic rocket engine, often called the plasma rocket engine (fig. 15). In this engine, the propellant gas is ionized to form a plasma, which is then accelerated rearward by electric and magnetic fields.

**A** plasma is merely an ionized gas, that is, a gas in which electrons have been removed from many of the atoms. In a neutral atom, such as those comprising the incoming propellant gas, there are as many electrons around the nucleus **of** the atom as there are protons in the nucleus. Neutrons have no electric charge, protons have one positive charge each, and electrons have one negative charge each. With an equal number **of** positive and negative charges, the atom is electrically neutral. This is the normal state for atoms in a gas at ordinary temperatures. In figure 16, if one electron were knocked loose and away from the atom, the atom would have two protons and only one electron. Thus, one positive electric charge is left. The charged atom is called an ion.

The atom shown in figure 16 is a helium atom. It has a simple electronic structure. Other atoms have many more protons, neutrons, and electrons, but the principle of ionization is the same. ***An*** atom may be multiply ionized by the loss of several electrons. In a plasma, the electrons and the ions are swirling about in a tremendous disorganization much like atoms in a gas. The plasma can conduct electric current just as a copper wire can conduct current. It is this conductivity that makes it possible to accelerate the plasma as shown in figure **15.** When an electric current is made to pass through the plasma in the presence of a magnetic field, a force is exerted on the plasma. Because of this force, the plasma is accelerated rearward to a high exhaust velocity. Thus, a plasma rocket engine is quite similar to an electric motor with the plasma taking the place of the moving rotor.

**A** plasma engine is very complicated, and all the physical mechanisms occurring in it are not yet understood. This type of engine, however, has promise of being a good electric rocket engine, and research on several designs is continuing.

The third type of electric rocket engine is the electrostatic rocket engine, sometimes called

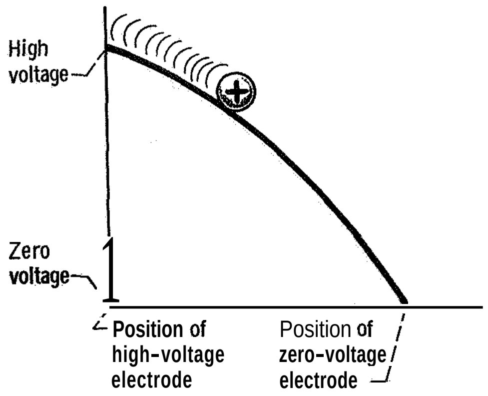



Figure 18.

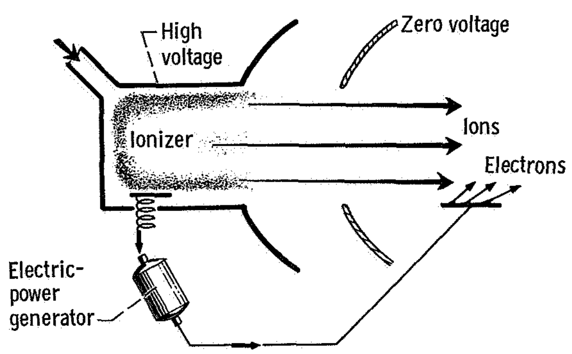



Figure 19.

an ion rocket engine (fig. 17). As in the plasma rocket engine, propellant atoms are ionized by removing an electron from each atom. In the electrostatic engine, however, the electrons are entirely removed from the ionization region at the same rate as ions are accelerated rearward. The ions are accelerated by an electric field to a high exhaust velocity and thereby produce thrust.

A voltage diagram may better illustrate how the ions are accelerated (fig. 18). A positively charged particle will always tend to fall down a voltage "hill." Scientists call this hill the potential and define voltage as the difference in potential. Because the final speed of the ion depends on the height of the voltage hill, the exhaust velocity can be controlled by adjusting the voltage of the high-voltage electrode. The ionizer is at the same voltage as the high-voltage electrode. A potential diagram such as shown is merely a way of showing electric fields, which are actually invisible.

The electric field exerts a force on electric charges, and, therefore, it also exerts a force on particles that have an electric charge. The steeper the hill, the greater the voltage, and the greater the force. Electric fields are just as mysterious as gravitational fields. Scientists cannot really explain why these fields exist, but they can predict what will happen to charges or masses in them.

The electrons freed from the propellant atoms must be removed from the ionizer and ejected from the spacecraft in order to maintain the ionizer in the electrostatic rocket at a high voltage (fig. 19). The positively charged ions like to fall down the potential field, but electrons have a negative charge, and, therefore, they like to travel up the potential field. At the ionizer, the electrons are already at the top of the potential hill; they must be forced to go down against their natural inclination. Electric power is required for this action. The electric generator is a kind of electron pump, which labors furiously to pull the freed electrons down from the ionizer. Once the electrons are forced down to zero potential, they can be ejected from the engine. In fact, these electrons must be injected into the ion exhaust beam in order to neutralize the accumulated positive electric charge in the exhaust. If this neutralization were not accomplished, the ions in the beam would stop each other, and a gigantic traffic jam of ions would occur. Without the added electrons the engine would stop, and no more thrust would be produced.

The thrust of an electrostatic rocket engine may be explained in another way (fig. 20). Neutralization of the exhaust beam levels the potential field behind the engine. When maximum thrust occurs, the potential field is flat at the ionizer and curves downward with the steepest slope at the

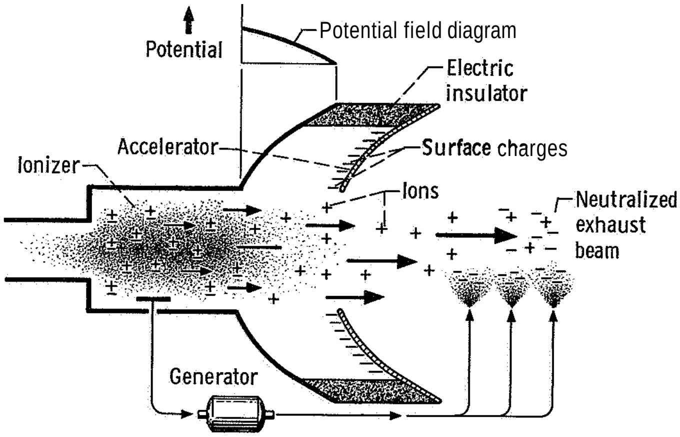


Figure 20.

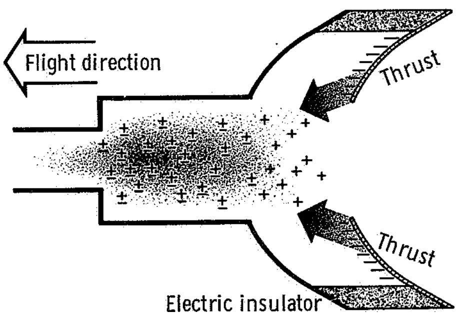


Figure 21.

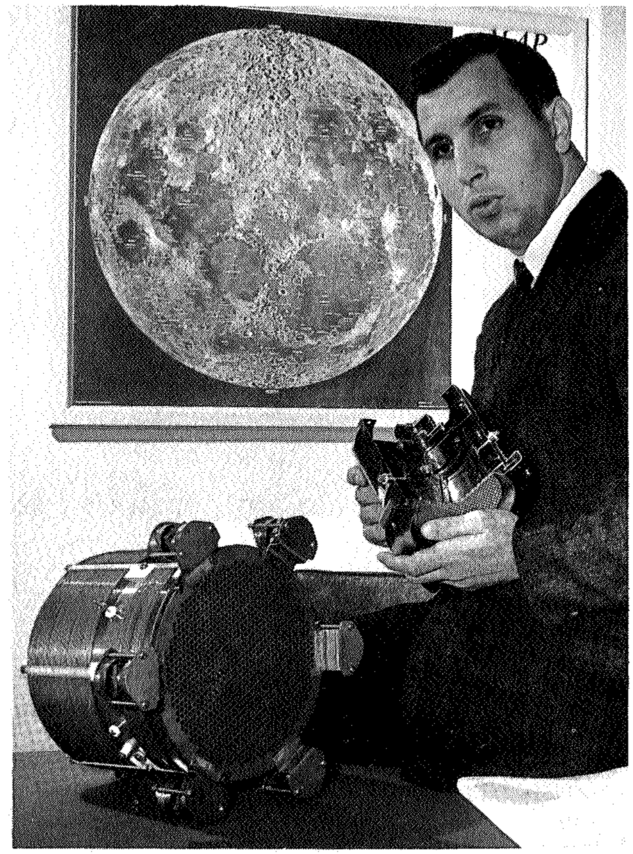


Figure 22.

end of the accelerator. Behind the engine, the potential field is flat. When a potential-field slope touches an electrode, surface charges will be present; this happens at the end of the accelerator just inside the engine as shown in figure 21. For the field in the ion engine, these surface charges are negative. The electrostatic attraction between these negative surface charges and the positive ions rushing through the accelerator result in a force on the accelerator electrode. This is the thrust force in the electrostatic rocket engine.

An experimental ion engine that uses mercury as a propellant is shown in figure **22.** When heated, mercury evaporates and forms a vapor, which is fed into the ionizer. There an electron is knocked out of the mercury atom to form an ion. This ionization is accomplished in a gentle electric discharge (fig. **23)** wherein electrons in the discharge hit electrons in the atom and displace them from the structure of the mercury atom. The electrons and the mercury ions form a plasma in the ionization chamber. The electric field draws ions from the plasma. These ions are then accelerated out through many small holes in the zero-voltage electrode.[6] This engine design was conceived by **Mr.** Harold R. Kaufman, a research

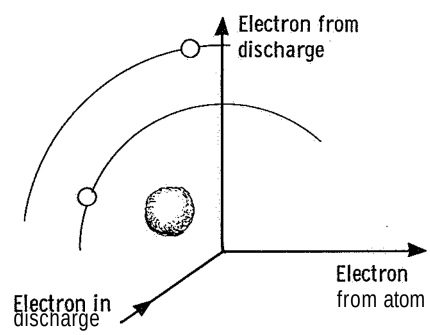


Figure 23.

[6]This electrode actually has a negative voltage to repel the negatively charged electrons in the exhaust beam. **If** this electrode were not used, the electrons would rush back into the engine and cause a "short circuit."

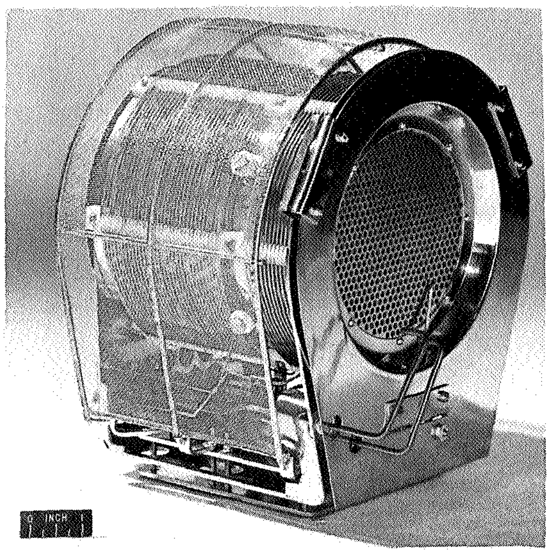


Figure 24.

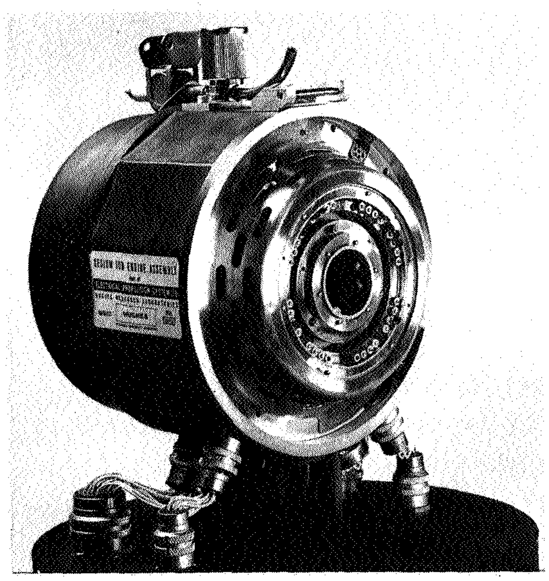


Figure 25.

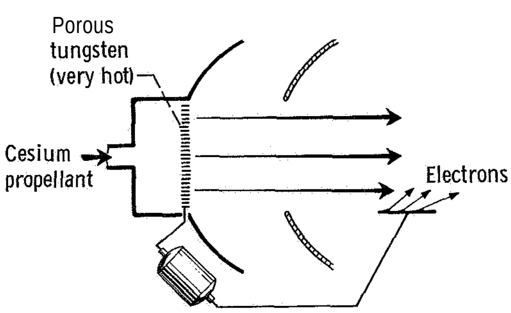



Figure 26.

scientist at the NASA Lewis Research Center. It is the most efficient electric rocket engine today. Tests have shown that it can operate at efficiencies near 90 percent.

Electrostatic rocket engines are fairly advanced in research and development. On July 20, 1964, two of these engines were tested in space. One of these was the mercury-propellant ion engine already described. The flight version of this engine is shown in figure 24. The other engine was a cesium-propellant ion engine developed by the Hughes Research Laboratories, Malibu, California, under NASA contract (fig. 25). In this engine, cesium atoms are ionized by contact with white-hot tungsten surfaces (fig. 26). (Cesium, a soft, silvery metal, melts readily.) The electrons taken from each atom are trapped in the tungsten and drawn away through wires by the electric generator. The cesium ions are accelerated away from the tungsten surface by the electric field. Both engines were mounted in the NASA SERT[7] capsule (fig. 27). This capsule was launched with a Scout solid-propellant rocket into a ballistic trajectory. The primary purpose of SERT was to test the performance of the electrostatic rocket engine in space. These engines have been operated on the ground for hundreds of hours in vacuum tanks, which simulate the environment of space. The engines operate quite well in vacuum tanks, but the vast reaches of space cannot be fully simulated in any tank. For example, the cesium or mercury ions from the engines strike the walls of the vacuum tank and may knock many electrons loose from the walls (fig. 28). These electrons may enter the exhaust beam and neutralize the ion space charge described previously. When this neutralization occurs, it is difficult to tell whether the electrons from the engine neutralizer are doing their job of neutralizing the ion beam.

Because electric rocket engines have only a small thrust, the 50-minute SERT I ballistic flight would not have been long enough for the engine thrust to push the

[7] Space Electric Rocket Test.

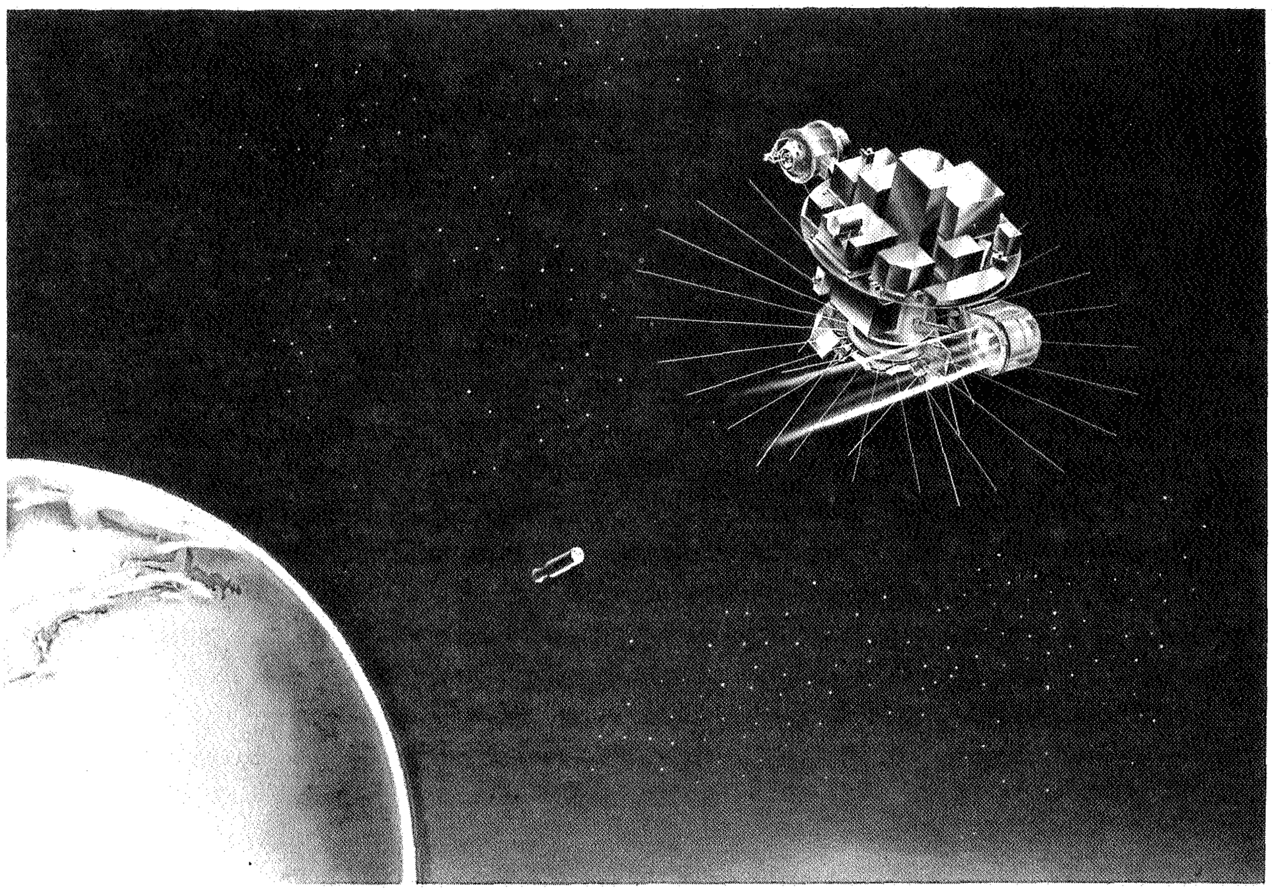


Figure 27.

spacecraft one way or the other. Therefore, the engines were so mounted on arms that their thrust would spin the top-like spacecraft. Thrust output of the Lewis built electron-bombardment engine was determined by measuring the change in spin rate of the capsule. The mercury electron-bombardment engine aboard SERT I operated as expected and produced thrust. Thus, the principle of neutralization was proved.

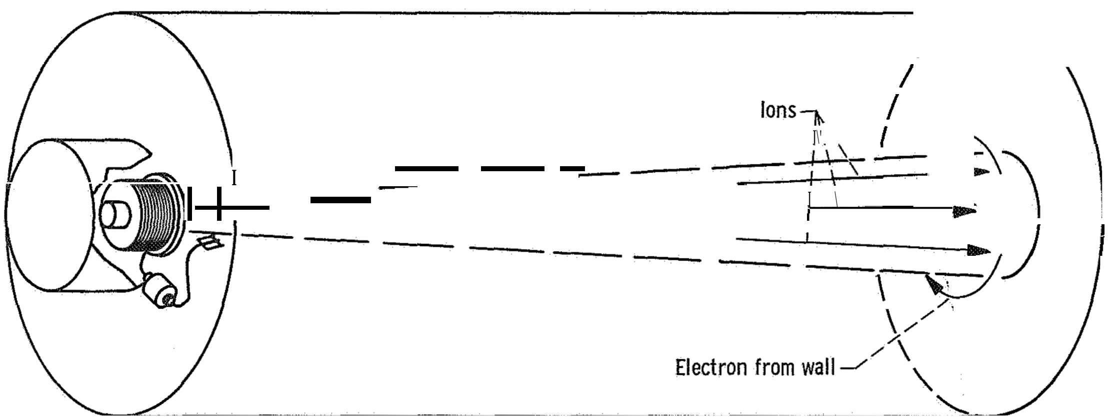



**Figure 28.**

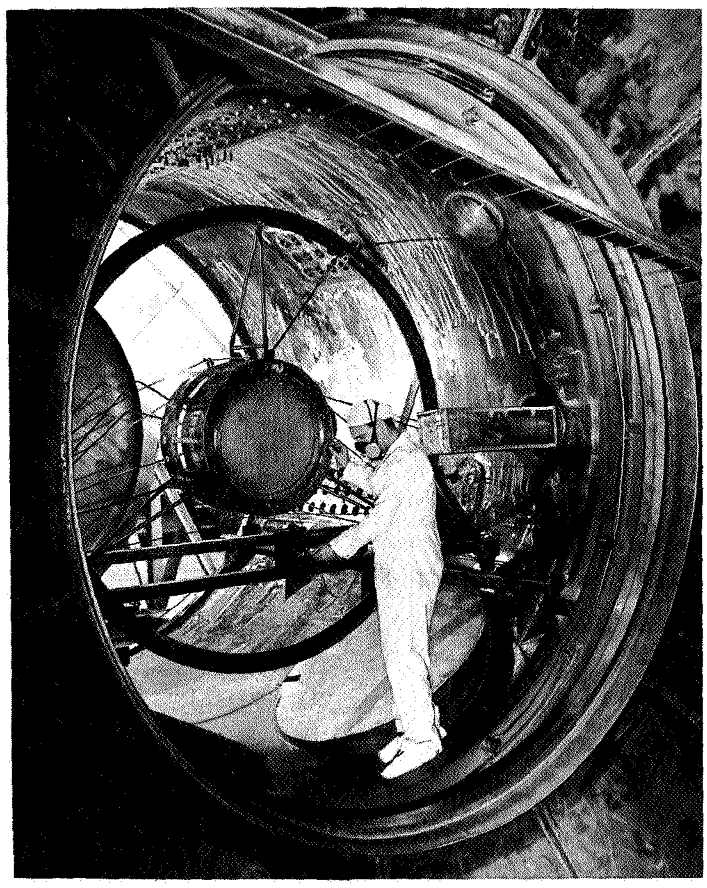


Figure 29.

The cesium-propellant ion engine aboard SERT I did not operate because of a breakdown in the high-voltage system. On August 29, 1964, however, a cesium-propellant ion engine was operated successfully in a similar space test by the U. S. Air Force. The Air Force test engine was developed by Electro-Optical Systems, Pasadena, California.

Electric engines with higher efficiencies may be possible with advanced designs, and research is progressing on possible engine concepts. One such advanced rocket is the colloidal-particle engine. This electrostatic engine uses a propellant of microscopic particles that each consist of many molecules. Voltages required by this engine may be as high as 500,000 volts.

Much research has been done on electric rocket engines. Much more remains to be done on these revolutionary thrust devices. Flight engines have been built and flight-tested. These first engines only served the purpose of flight tests. Bigger and better ones will be needed for the long journey to other planets. Lewis is pursuing this long-range goal in two main areas. A thrustor-scaling program is exploring the possibility of larger size electron-bombardment engines. This program involves designing, building, and testing larger and larger engines. The 50-centimeter engine shown in figure 29 is one of the larger-size engines built in this program.

The second major area of work is concerned with extended testing of engine components. Because electric rockets must continue to thrust for months or even years, a high degree of reliability is necessary. Much additional work by scientists and engineers is required before such reliable operation can be obtained. Present engine designs are adequate for powerplants now under development. Much lighter engines will be required for the advanced electric powerplants to be discussed later.

## SATELLITE PROPULSION WITH ION ENGINES

One of the first actual applications of electric rocket engines may be the control of satellites. Some satellites must be held in specific attitudes so that their instruments, antennas, or solar cells will work correctly. Other satellites must also be held in particular positions over Earth, For example, "synchronous" satellites must be held directly over a single spot on Earth. These are also called "24-hour satellites" because they will orbit at such an altitude over the equator

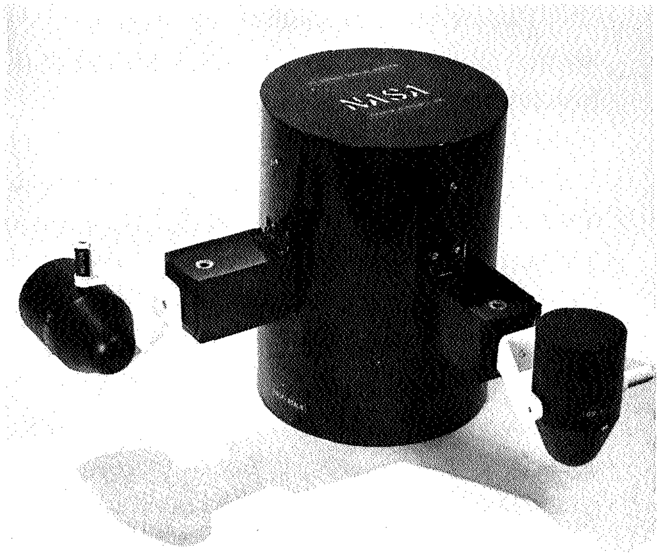


Figure 30.

that the satellite revolves around the center of the Earth once every 24 hours. Since the Earth also rotates once in a 24-hour period, the orbiting satellite is stationary in relation to Earth.

Forces tending to disturb the attitude or position of a satellite are many; they are due to the oblateness of Earth and the gravitational attractions of the Sun, the Moon, and other celestial bodies. These forces are small, but over a period of days or weeks they can appreciably affect the satellite. Ion rocket engines may be well suited to overcoming these perturbing forces on satellites. The ion rocket thrust is small, but so are the perturbing forces.

Ion engines have a low propellant consumption because of their high exhaust velocities. Solar cells can provide enough electric power to run the ion engines. For these reasons, ion engines could be satisfactorily used for attitude control and position keeping of long-life satellites.

A prototype ion-engine propulsion system for satellites has recently been built for NASA by Hughes Research Laboratories. This prototype system is being tested and evaluated. It could be integrated with a satellite as shown in the Hughes model (fig. 30). Such satellites could be used for weather observation, astronomy, geophysical measurements, or world-wide communication. Other systems using various thrustor types are also being investigated.

## SPACE PROBES WITH ELECTRIC PROPULSION

Interplanetary and deep-space probes are important not only to prepare the way for manned flight, but also to gather scientific information on the universe. With the large payload capacity of electric spacecraft, it will be possible to propel completely instrumented probe vehicles into satellite orbits about the planets and to land instrument packages on the surfaces. Even the distant planets such as Jupiter, Saturn, Uranus, Neptune, and Pluto can be reached with electric-powered space probes.

Nuclear turboelectric power generation systems now under development may have enough power to propel space probes to Mars and Venus. The model shown in figure 31 is a design concept for a nuclear-turboelectric powered spacecraft suggested by the Aerojet General Corporation.

Much lighter nuclear-fission - turboelectric powerplants will be needed for flights to Jupiter and beyond. Advanced powerplants would make such flights possible, in addition to shortening the flight time considerably. Figure 32 illustrates the performance of electric spacecraft for Mars and Saturn orbiting instrumented probe vehicle missions. These calculations are based on a starting mass of 27,000 pounds in a satellite orbit about Earth, which is roughly the orbital payload capability of one of the NASA Saturn booster rockets. These graphs also illustrate that payload must be sacrificed to gain faster flight times. The advantage of lightweight powerplants is also apparent.

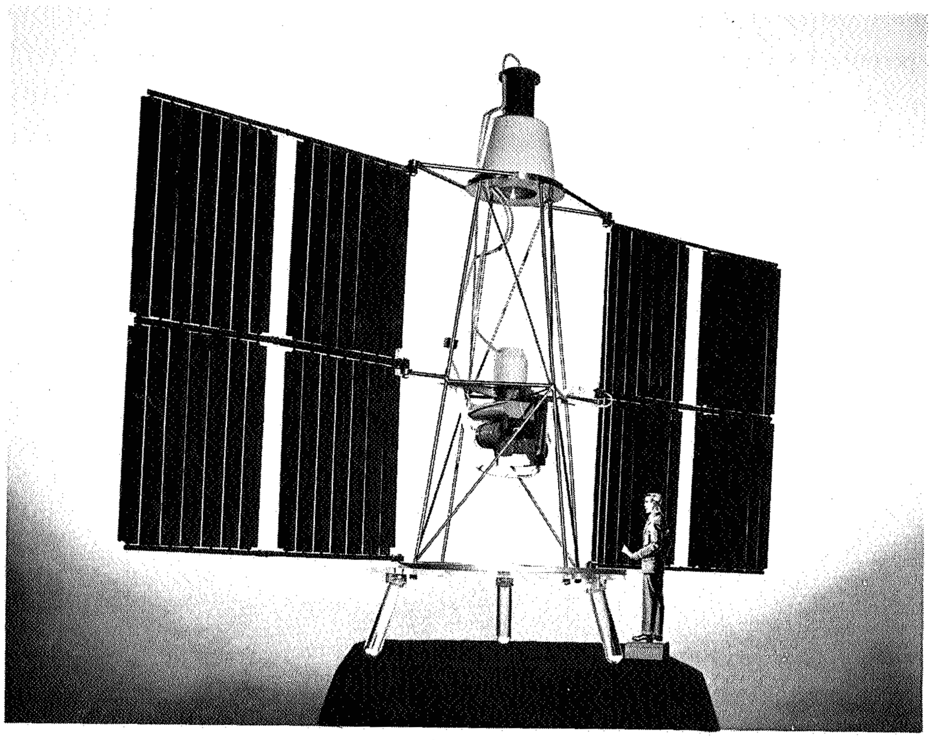


Figure 31.

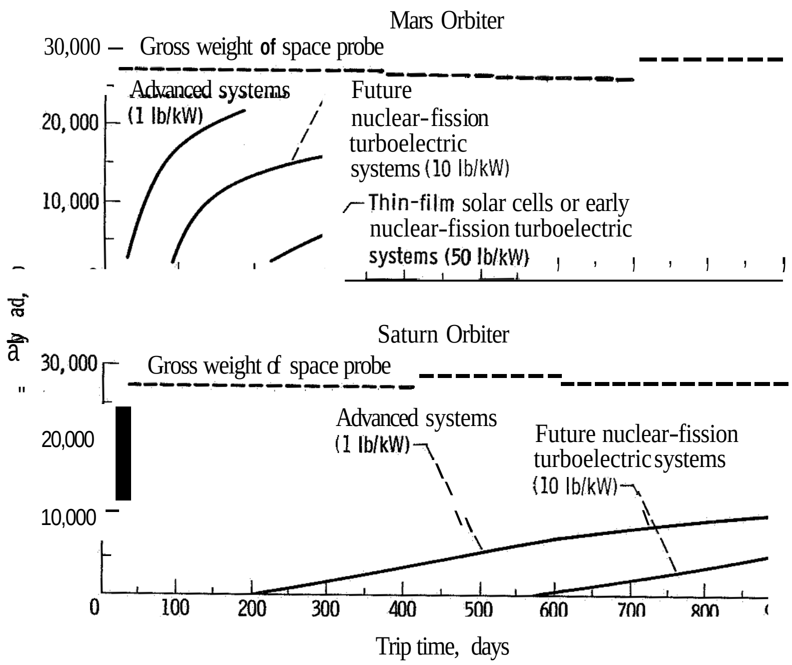



Figure 32.

## ROUND TRIP TO MARS WITH A NUCLEAR-FISSION TURBOELECTRIC SPACECRAFT

***An*** electric-powered spacecraft to carry men to Mars and back to Earth might look like that depicted in figure **33.** This design is only conceptual. There are no plans to build such a ship as yet. Space-flight scientists and engineers make such conceptual designs to determine how parts would fit together, to make weight estimates, and to establish what special problems might require research. This ship would carry an eight-man crew to Mars and back to Earth again in 500 days. It would be 400 feet long with various component weights as shown in the table.

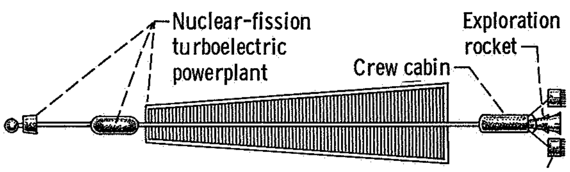


Figure 33.

| Component | Weight, lb |
|---|---|
| Return payload (cabin, etc.) | 50,000 |
| Supplies for crew (10 lb/(day/man)) | 40,000 |
| Exploration rocket (used on Mars) | 40,000 |
| Electric powerplant | 90,000 |
| Propellant | 230,000 |
| Total vehicle weight | 450,000 |

For the same mission, a chemical rocket would have to weigh about 8,000,000 pounds, although some recent calculations suggest that the weight of the chemical-rocket system might be reduced to as little as 1,000,000 pounds by using unique trajectory concepts. Such unique trajectories could, of course, be equally beneficial to electric propulsion vehicles. The comparison shown in figure **34** illustrates the tremendous advantage of electric spacecraft. The boosters shown are NASA Saturn V chemical rockets of the kind to be used in the Apollo flight to the Moon. Each booster rocket can carry only a specific weight into orbit. A total of **34** booster rockets would be required to launch parts of the chemical rocket spacecraft into orbit. If the chemical rocket weight could be reduced to 1,000,000 pounds, only five boosters would be required. Once in orbit all these parts would have to be assembled before the spacecraft could begin its round trip to Mars. Only two booster rockets would be needed to launch component parts of the electric spacecraft into orbit.

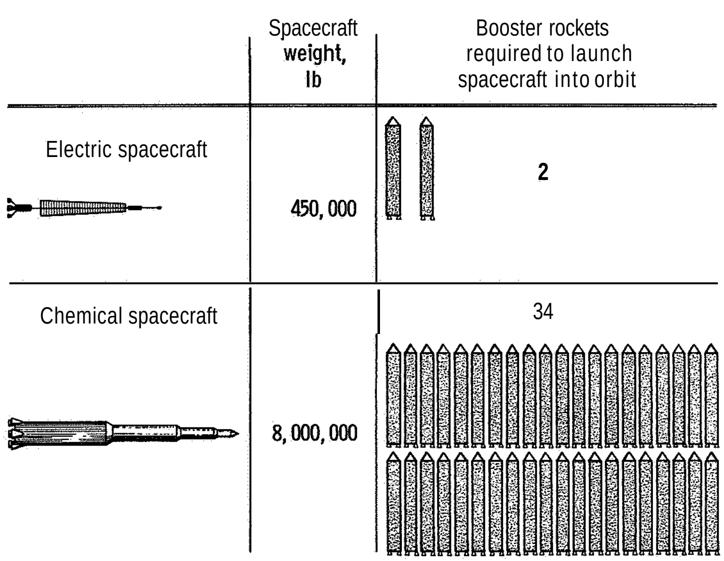


Figure 34.

Design details of the crew's cabin are undetermined at the moment. The Mercury, Gemini, and Apollo spacecraft will provide much of the knowledge concerning what is needed to keep the crew safe and comfortable during long space flights. Perhaps an orbiting space station will be built before man flies to Mars; this space station would help too, but studies for the **Mars** trip will begin much before these events occur. Even before men fly to the Moon, instrumented probes will make many measurements of conditions and hazards along the path. Micrometeoroids are one hazard to spacecraft. These tiny chunks of matter travel so fast that they can puncture metal walls. Instrumented probes will measure the number, size, and speed of micrometeoroids, and this information will help in the design of space cabins.

Radiation damage presents another danger. It can seriously affect the cells in man's body. Cells may become temporarily damaged, may become cancerous, or may even die. Many sources of radiation will surround the astronaut on board a spaceship: nuclear powerplants, Van Allen belts, cosmic rays, and solar flares. Of these, giant solar flares may be the most dangerous. They can be very intense and their occurrence cannot be predicted accurately. Radiation from solar flares consists primarily of very high speed protons (ionized hydrogen atoms), which are thrown out from the Sun. When these protons smash into matter, intense secondary radiation is generated. The primary protons and the secondary radiation can cause sickness or death, The crew must be well protected against this dangerous radiation. One way to protect them is to construct very thick and heavy walls or shields surrounding their cabins (fig. 35). The weight of shielding required may be reduced by storing the propellant around the cabin. Perhaps some of the crew supplies, such as water, could help shield them too. Some scientists have suggested that magnetic fields could be used €or this purpose, but they would have to be extremely strong, so strong that superconducting magnets would be needed.

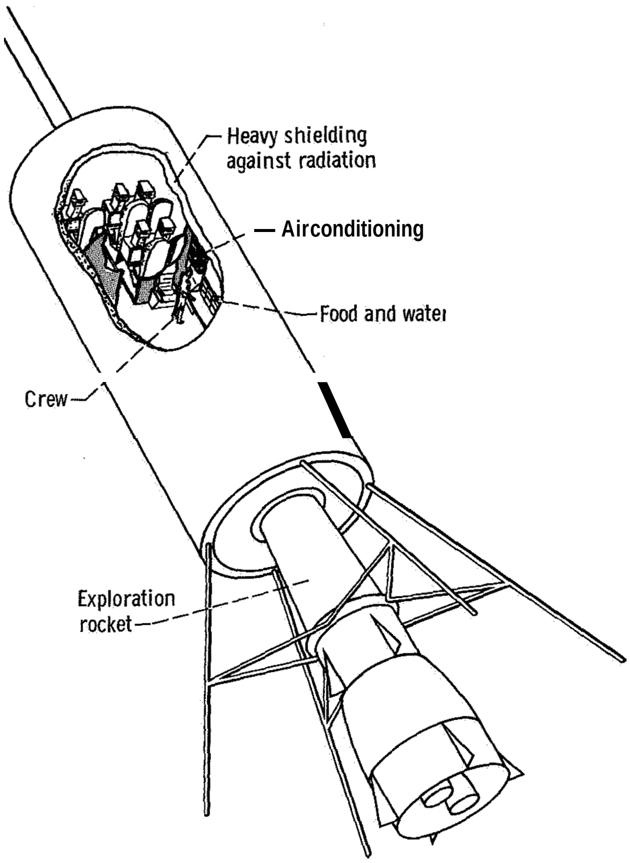


Figure 35.

These dangers, and perhaps dangers as yet unknown, must be studied with instrumented probes before journeys to the planets can be made. With sufficient measurements, engineers and scientists will be able to design safe cabins for the crew.

Electric power on board the Mars-bound spacecraft might be generated by a nuclear-fission turboelectric system. Energy is released in the nuclear reactor when atoms of the nuclear fuel break apart. This breaking apart is called fission. Only certain kinds of atoms under the right conditions will undergo fission. The nucleus of the uranium atom is very large (many protons and neutrons) and is just on the verge of breaking apart. If an additional neutron enters the nucleus, it can no longer contain all its parts. The nucleus breaks in two, and two neutrons fly off. When this fission occurs, a tremendous amount of energy is released. This is part of the energy that the nucleus had been using to hold itself together. When a sufficient number of uranium atoms are put together in the reactor, enough neutrons enter different uranium nuclei that a continuous action results (fig. 36). The released energy turns into heat, and the fission reactor becomes very hot. A fluid passing through the reactor will absorb the reactor heat and carry this heat to

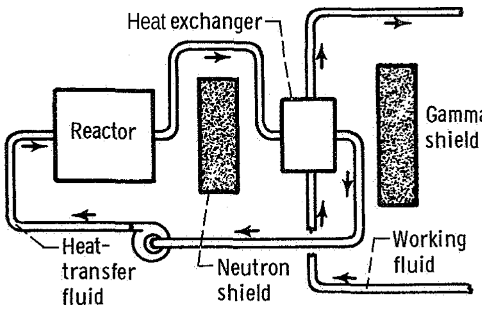



Figure 36.

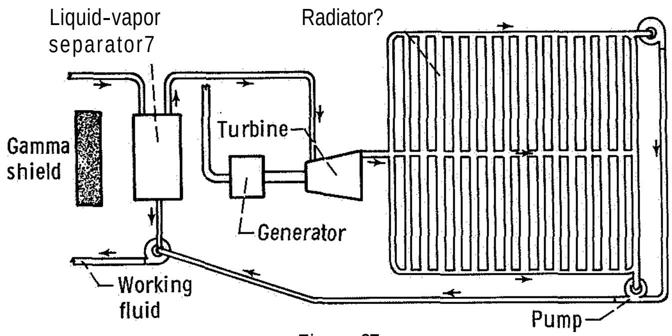



Figure 37.

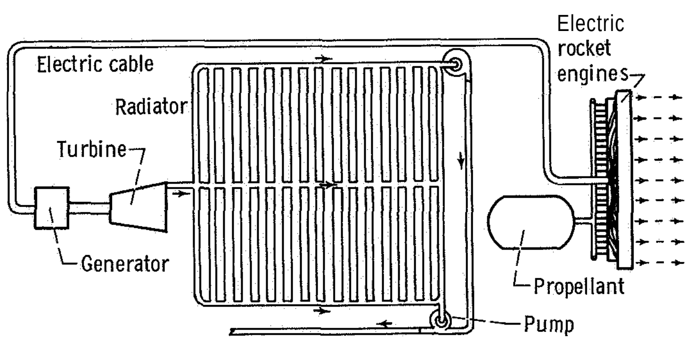



Figure 38.

a heat exchanger. A neutron shield must be used to protect the crew from the dangerous neutrons escaping the reactor. The heat-transfer fluid will be made radioactive as it passes through the reactor; for this reason the shield against dangerous gamma rays is positioned as shown in the figure. Heat is transferred from the heat-transfer fluid to the working fluid. The working fluid is not made radioactive by the gamma radiation and, therefore, need not be shielded after it pasges through the gamma shield. The working fluid is heated to such a high temperature that it turns into vapor. This vapor is also at a high pressure and thus can blow through a turbine swiftly. In passing through the turbine, the vapor blows on the turbine blades and spins the turbine on its shaft, much as air spins a windmill. The spinning turbine shaft drives the electric generator to produce electricity, used to run the electric rocket engines.

Vapor being exhausted from the turbine must be cooled and condensed before it flows back to the heat exchanger, where it is heated and vaporized again. Because space is a vacuum, this cooling must be accomplished with a large radiator (fig. 37). There is a greater probability of a micrometeoroid hitting a large area than a small one, and, therefore, the giant radiator must have tube walls thick enough to prevent punctures by micrometeoroids. Punctures would allow the working fluid to leak out. If this leaking occurred, the spacecraft would stop thrusting and go into orbit around the Sun forever. Thick tube walls make the radiator heavy. Since very lightweight powerplants are needed for space flight, scientists are trying hard to design better, lighter radiators.

Electric power from the nuclear-fission turbogenerator system would be used to run the electric rocket engines (fig. **38).** Clusters of electric rocket engines must be used to provide enough thrust. If current electron-bombardment engines were used, a great many would be required. Ion engine experts believe that larger engines can be built; thus, the number required would be reduced.

In an earlier section, a description was given of an electric spacecraft flight from Earth to Mars. The ship spiraled out from Earth, swung around and out to meet Mars, and spiraled into Mars (fig. 39). This electric spacecraft would continue to orbit around Mars during the exploration period. Landing on the surface of Mars is not possible with such a low-thrust nuclear-

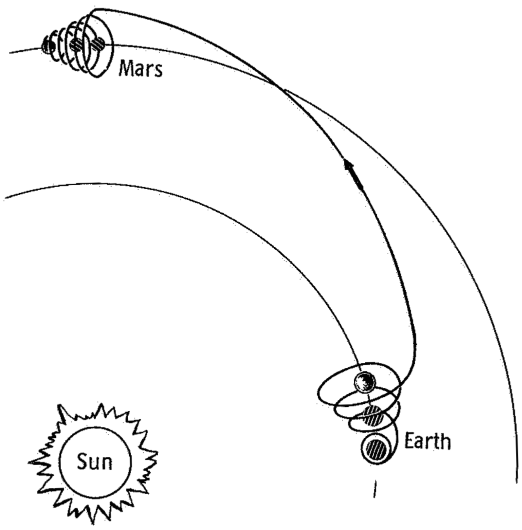



Figure 39.

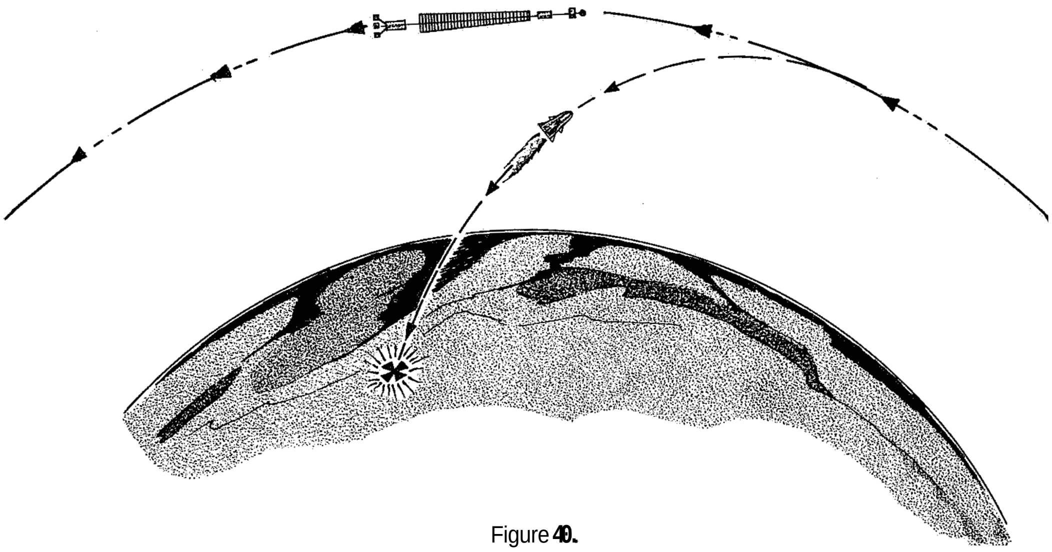


Figure 40.

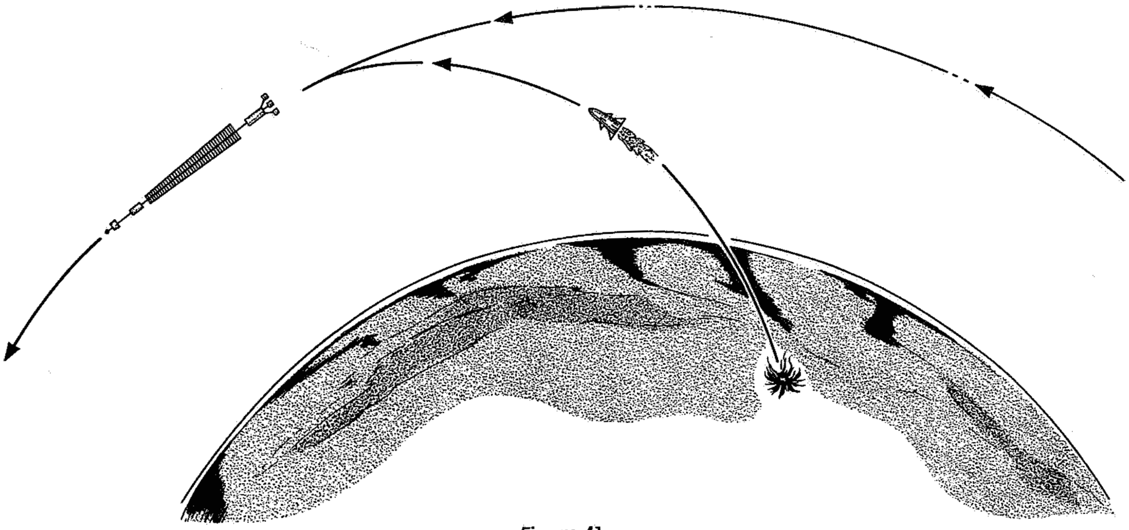


Figure 41.

turboelectric spacecraft. If the surface of Mars is to be explored, some of the crew must descend from orbit in a chemical rocket (fig. 40). The nuclear-fission - turboelectric spacecraft would continue to orbit Mars until its crew returned in the chemical rocket (fig. 41). With the crew back on board, the electric spacecraft would spiral up and out of Mars' gravitational field (fig. 42).

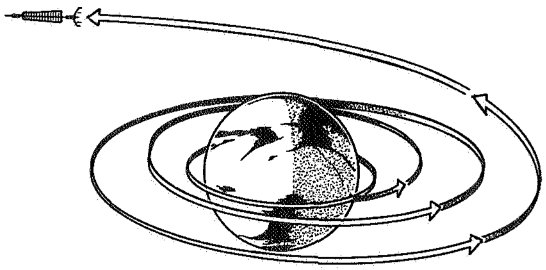


Figure 42.

Both Earth and Mars are moving during the trip to Mars and the exploration of Mars. When the ship leaves Mars for the return trip, the two planets will be in the position shown in figure 43. The Earth is orbiting the Sun faster than Mars, and, therefore, the ship must speed up to catch Earth. In fact, Earth is going so fast that the ship must take a shortcut as illustrated (fig. 44). The shortcut passes inside of Earth's orbit, and the ship will then be going too fast. It must be turned around in order to use the electric rocket engines as brakes (fig. 45).

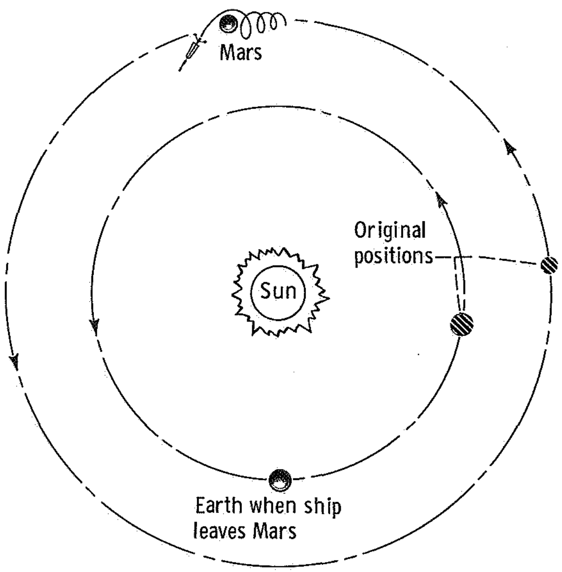



Figure 43.

With proper navigation, the spacecraft can catch up with Earth. It will then spiral down into an orbit about Earth using the electric rockets as brakes (fig. 46). Once in Earth orbit, the crew can land in reentry capsules similar to the Mercury or Gemini vehicles. These reentry vehicles could be parts of the original spacecraft cabin.

This is the story of how man might make trips to Mars and return. Of course, the trip has not happened yet - it will be some time before such trips can be made. The electric spacecraft used in this story is

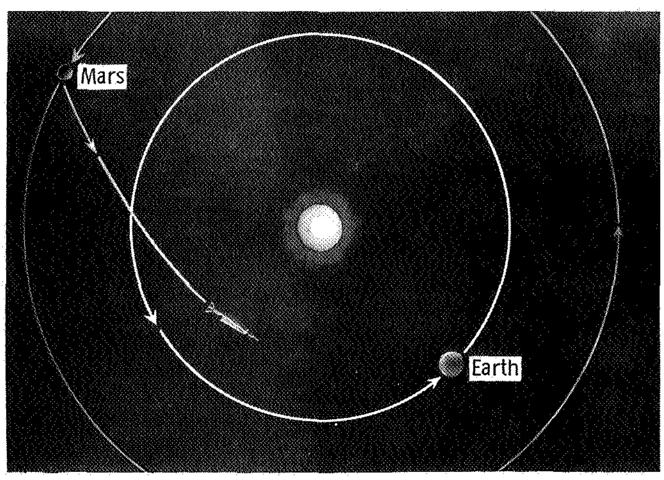



Figure 44.

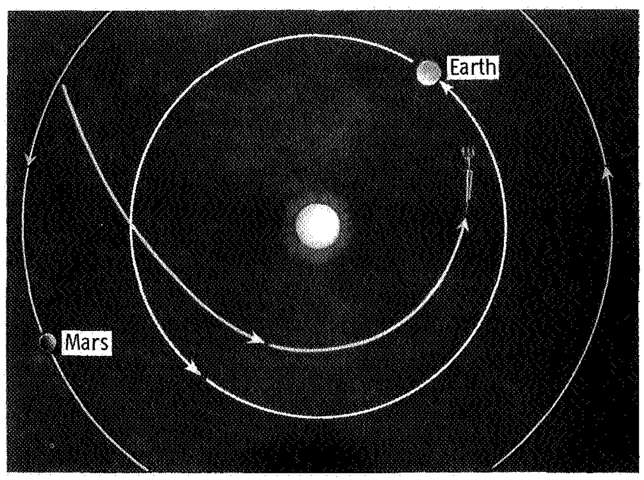
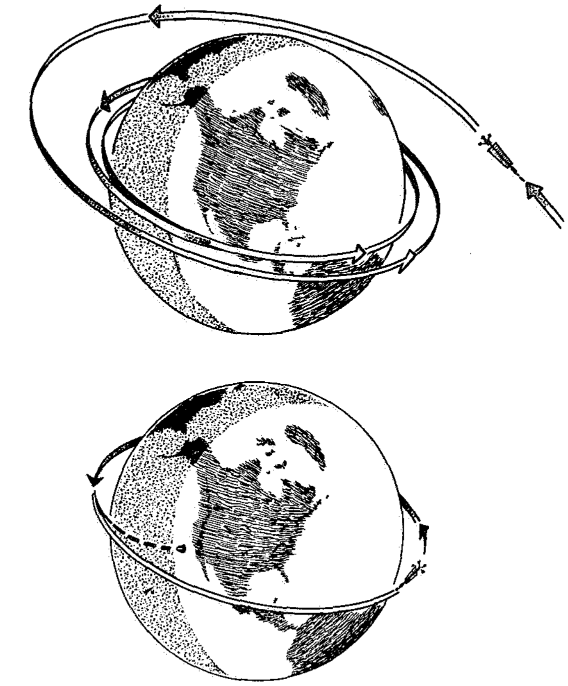



Figure 45.



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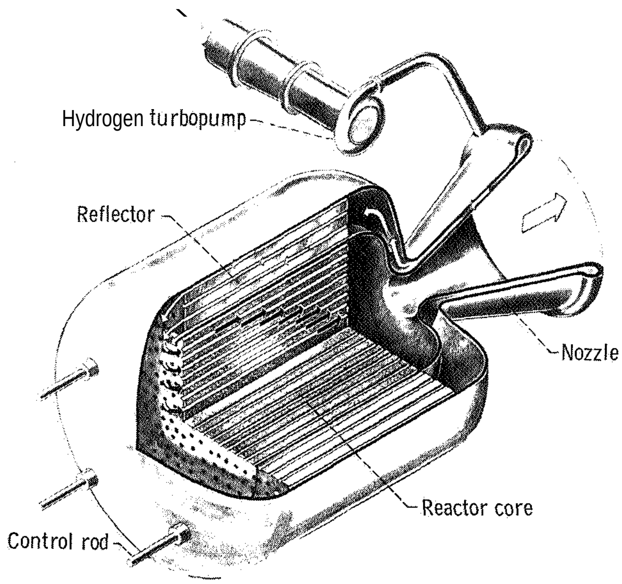



Figure 47.

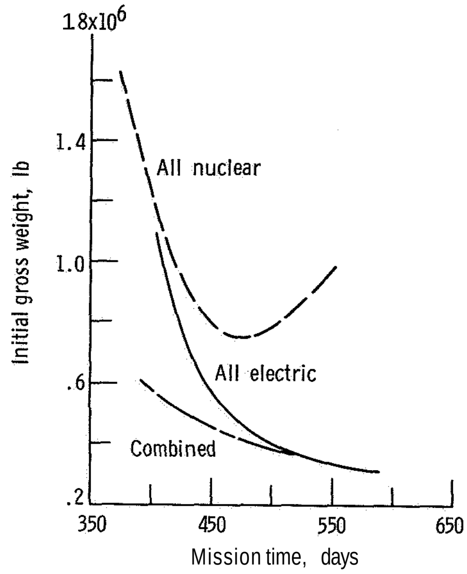



Figure 48.

merely a conceptual design based on present knowledge. The ship used in the future may well be different from this one. In any event, the basic principles set forth in the story are true, and as such, form a general framework for the work of tomorrow.

## THE NUCLEAR ROCKET

Nuclear rockets as well as electric rockets are capable of long space flights. As implied in their name, nuclear rockets (fig. 47) use nuclear energy to produce thrust. The intense heat of nuclear fission reactors is used to heat a propellant gas that then rushes out the rear exhaust nozzle to create thrust. Dissociation and materials limit the exhaust velocity of the nuclear rocket just as in the chemical and the electrothermal rockets. A lightweight propellant such as hydrogen can be used to produce an exhaust velocity two or three times that of the chemical rocket. Nuclear rockets can make fast round trips to Mars. Figure 48 is a comparison of the initial weight required for a seven-man mission to Mars for a nuclear rocket, an electric rocket, and a combined nuclear and electric system. The comparison shown is calculated from theory. It may change in favor of one or the other of these rockets as scientists and engineers learn more from research and development.

## A RADIOISOTOPE ELECTROSTATIC PROPULSION SYSTEM

Lightweight electric powerplants are one of the most important requirements for electric space propulsion. With lightweight electric powerplants, fast flights of large payloads could be made to the farthest reaches of the solar system. This point is illustrated by figure 49, which is based on a one-way unmanned trip to the planet Saturn. Many space propulsion engineers believe it will be very difficult to build a nuclear-fission - turboelectric powerplant weighing only 10 pounds for each kilowatt of electricity it produces - a 20-megawatt powerplant could then weigh only 100 tons. How then can an advanced electric propulsion system weighing only 1 pound per kilowatt even be considered? Such lightweight systems do appear to be possible if new principles are used. The radioisotope electrostatic propulsion system is an example of such an advanced concept. Although a powerplant of this type has not been built as yet; a theoretical study has been made and the idea appears feasible.

In this propulsion system, the powerplant would be an "atomic battery," in which the nuclear energy of radioisotopes would be converted directly into electricity. Radioisotopes are atoms that have unstable nuclei; that is, the nuclei spontaneously emit particles and radiation to relieve their strained unstable condition. A simple example is the radioisotope of polonium ($Po^{210}$) (fig. 50). The nucleus of the polonium 210 atom relieves its instability by throwing off an alpha particle.[8] Thereby the polonium 210 atom changes into another smaller atom that is stable. Scientists call this emission the decay process. Emission is random; therefore, all the emission does not occur at once. For example, in a large group of polonium 210 atoms, one-half of them will decay within

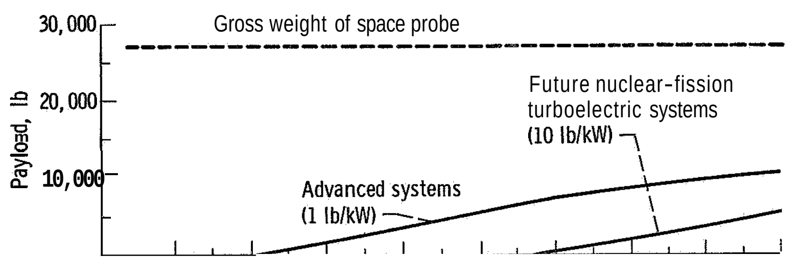



Figure 49.

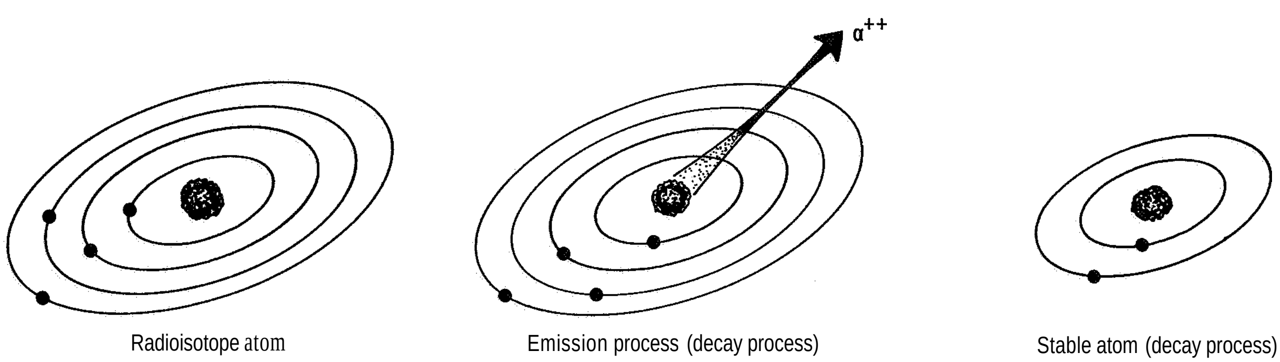



Figure 50.

[8]The alpha particle is a helium nucleus, that is, a helium atom without electrons.

138 days. In another 138 days, one-half of the remaining polonium 210 atoms or one-fourth of the original number will have decayed. Because of this decay rate, the energy in a mass of radioisotopes is not all released at once. Instead, energy is produced at a certain rate. It is important to note here that this energy release cannot be controlled. Once the radioisotope atoms are formed, they begin to decay and cannot be stopped.

The energy released by radioisotope decay is in the form of very-high-speed particles or radiation. In the case of polonium 210, an alpha particle is thrown off at speeds near 36,000,000 miles per hour.

Since alpha particles are doubly ionized helium atoms, they have a double positive charge. Particles with a positive electric charge like to roll down electric fields. If a positively charged particle has enough speed, however, it can travel some distance up an electric field (fig. 51). The height, or voltage, at which the particle slows to a stop is dependent on the speed it had at the beginning - the higher the speed, the higher the particle can go. The alpha particles from polonium 210 decay have enough original impetus to travel against potential fields of 2,650,000 volts.

The kinetic energy of the alpha particles from polonium 210 decay can be converted to electricity in the following way (fig. 52): When alpha particles are emitted from the radioisotope material, a net negative charge in the form of free electrons is left behind. If the alpha particles are shot up a potential hill and collected at the top, a voltage will be generated between the radioisotope emitter and the collector. The electrons left behind in the emitter would like very much to run up the hill. In doing so, they are actually creating what is called electric current. Consequently, they can power electric rocket engines as they flow up the voltage hill.

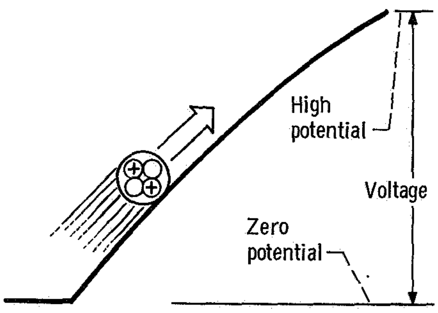


Figure 51.

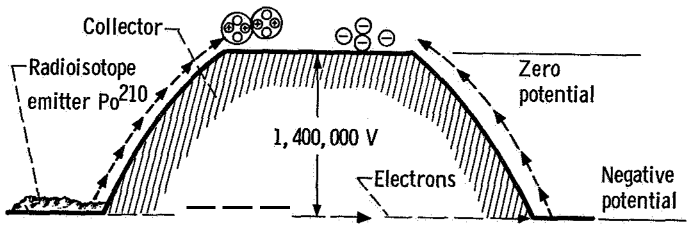


Figure 52.

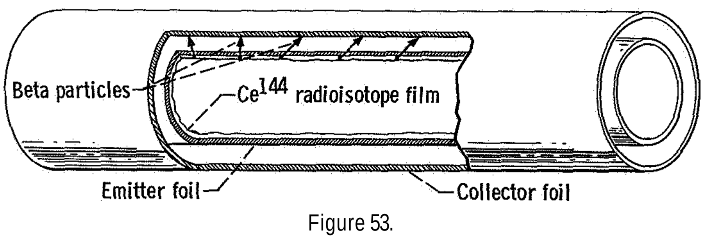


Figure 53.

Most radioisotopes are rare and expensive. Polonium 210 can be produced by neutron bombardment of bismuth; thus, if bismuth is used as a coolant for nuclear-fission reactors, small quantities of polonium 210 can be obtained as a byproduct. Other radioisotopes, such as that of cerium ($Ce^{144}$), are far more plentiful. The decay process of cerium 144, however, is complicated, and, therefore, for convenience polonium 210 is used here to demonstrate the principles of the atomic battery. The cerium 144 radioisotope would work in a similar manner, except that high-speed electrons called beta particles are emitted and the voltages would, consequently, be reversed.

Electric-potential diagrams are imaginary pictures to aid in understanding; a real atomic battery might look like the design shown in figure 53. The parts must be

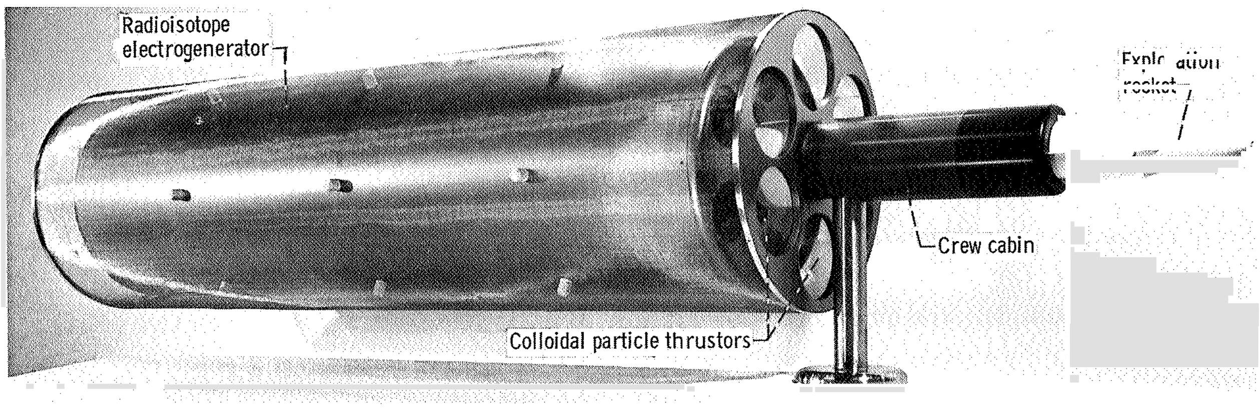



Figure 54.

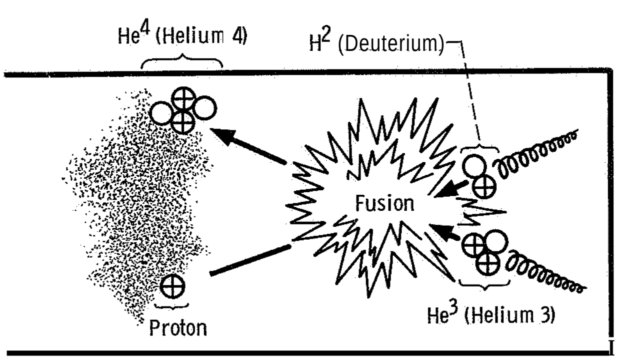
extremely thin in order to be very lightweight. Of course, the radioisotope film and the emitter foil must be very thin anyway to allow the decay particles to get through. The collector would be at zero voltage (space potential) and the emitter at about 700,000 positive volts. Because of this high voltage, a colloidal-particle electric rocket engine could be used with this radioisotope atomic battery.

A conceptual design of a spacecraft with a radioisotope electrostatic propulsion system is shown in figure **54.** Whether such a spacecraft could be built for manned flights is not known, however. This spacecraft would be about 270 feet long. An eight-man crew cabin is shown for comparison with the nuclear-fission - turboelectric spacecraft. According to theory, this radioisotope-electrostatic-propulsion spacecraft could make a trip to Mars and return in only 200 days, which is much faster than the nuclear-fission - turboelectric spacecraft.

## PROPULSION WITH THERMONUCLEAR FUSION

The thermonuclear-fusion system is still another advanced propulsion concept. The tremendous temperature from nuclear fusion would be used to heat a propellant to a very high temperature. The propellant would then rush out through a nozzle at a high exhaust velocity.

The intense heat of the Sun is generated by a thermonuclear fusion process in which the nuclei of atoms join together. When this fusion of nuclei occurs, a great amount of energy is released to heat the fusion-product gas to tremendous temperatures. For example (fig. **55),** deuterium and helium 3 may enter into fusion to form helium **4** and a proton. In equation form,




⊕ Proton O Neutron

Figure 55.

$$H^2 + He^3 \rightarrow He^4 + \text{proton} + \text{heat energy}$$

The deuterium and helium 3 must be at a very high temperature (i.e., moving at extremely high speed) in order for fusion to occur. The temper-

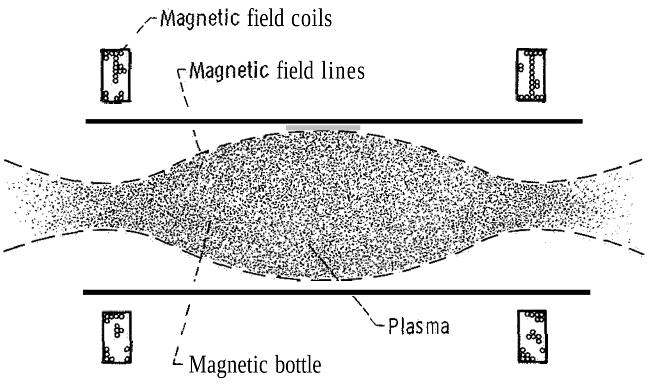



Figure 56.

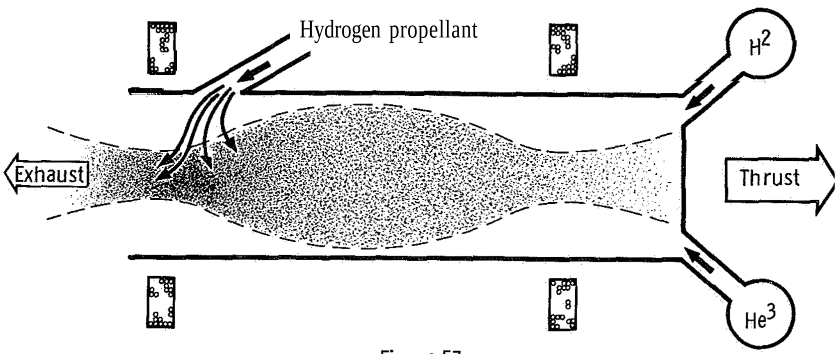



Figure 57.

ature must be about 100,000,000° C. The fusion products, helium 4 and protons, possess the tremendous energy released in the form of kinetic energy (high speeds). The goal of scientists at a number of laboratories is to devise controlled thermonuclear fusion, in which the fusion products give some of their energy to the fusion fuels so that the reaction can be self-sustaining and yet under control.

For the fusion process to be self-sustaining, the original nuclei must have an extremely high temperature (about 100,000,000° C). The gases involved in the fusion process might be kept at a high temperature by "bottling" them with magnetic fields (fig. 56). The fusion gases are at such a high temperature that they are ionized. Very strong magnetic fields can contain the fusion gases in the "magnetic bottle"; these fields would be of the order of several hundred thousand gauss. Producing such strong fields would require very heavy conventional magnetic field coils and much electric power. It is anticipated that superconducting magnets will be needed to produce such strong fields while a reasonable weight is maintained. Because some metal alloys have superconducting properties at temperatures near absolute zero, scientists are doing a great amount of research on this subject.

In the fusion rocket engine, a light propellant gas might be mixed with the fusion gases and thereby heated to a very high temperature. The heated propellant gas would then rush rearward through a magnetic nozzle, and the engine would produce thrust (fig. 57).

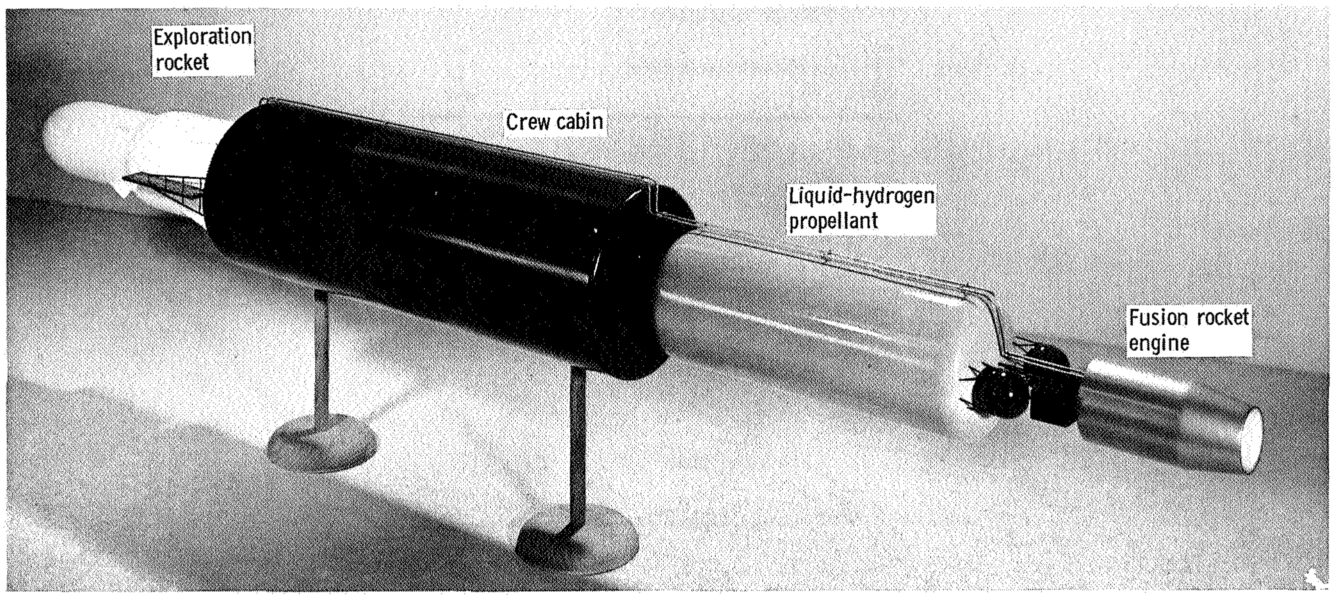



Figure 58.

Although controlled thermonuclear fusion has not yet been achieved, it is possible to conjecture what a **thermonuclear-fusion-powered** spacecraft would look like (fig. **58).** This ship would be about **150** feet long and would carry an eight-man crew. The round-trip time for the Mars exploration mission would be about 200 days.

## THE FUTURE

Space exploration beyond the Moon is a dream of the future, but it is a dream that draws nearer with each advance in propulsion research. Of the advanced propulsion ideas discussed herein, the ion engine is the nearest to practical use. It was test flown in space in **1964.** Ion engine systems for use in satellite control are now being developed.

Manned spacecraft for flights to the planets and instrumented probes for deep-space exploration will require large and lighter propulsion systems. Future research may make possible the use of radioisotope electrostatic and thermonuclear-fusion rockets. These are but two promising propulsion concepts; still better ones may be found.

The success of the early electric propulsion systems is only the beginning - a foundation upon which future space scientists are building advanced propulsion systems and vehicles for manned flight beyond the Moon.

# APPENDIX - DERIVATION OF ROCKET THRUST EQUATION

The thrust equation may be derived by applying Newton's third law of motion, which states that momentum must be conserved. In an inertial coordinate system as shown in figure 59, and at some specific point in time, the rocket has a momentum $M\bar{U}$. A differential mass of propellant $dm$ is ejected from the rocket with a velocity $\bar{v}$ with respect to the rocket.

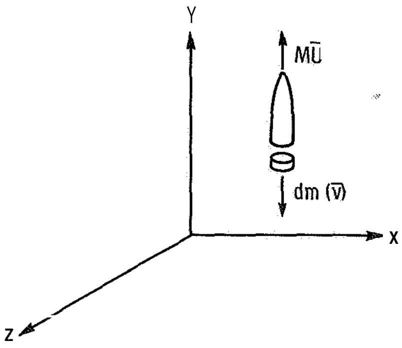


Figure 59.

By the law of conservation of momentum, the increase in the upward momentum of the rocket must equal the increase in the downward momentum of the propellant. Stated mathematically, this is

$$d(M\bar{U}) + (dm)(U - \bar{v}) = 0$$

Applying differential calculus to the first term and appropriate multiplication to the second gives

$$\bar{U}\,dM + M\,d\bar{U} + \bar{U}\,dm - \bar{v}\,dm = 0$$

Since the propellant mass ejected $dm$ originally came from the total mass of the rocket vehicle $M$, the change in mass of the rocket $dM$ is equivalent to the lost mass of the propellant $-dm$. Thus,

$$dM = -dm$$

Because of this relation, the former equation reduces to $M\,d\bar{U} = \bar{v}\,dm$.

Applying Newton's second law of motion, $F = Ma$, where acceleration $a$ is equivalent to $d\bar{U}/dt$, or the change in velocity with respect to time, we find that the force exerted on the rocket, actually the thrust, is equivalent to

$$M\,\frac{d\bar{U}}{dt}$$

but $M\,d\bar{U} = \bar{v}\,dm$; therefore,

$$\text{Thrust} = \frac{dm}{dt}\,\bar{v}$$

or thrust equals the propellant mass rate of flow multiplied by the exhaust velocity.

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